CONSTRUCTION INDUSTRY COUNCIL
建造業議會

Consultancy Report

Investigating the **Potential of Implementing Robotics and Automation** in the Context of Large-scale Housing Development for Hong Kong

Investigating the Potential of Implementing Robotics and Automation in the Context of Large-scale Housing Development for Hong Kong

香港大規模房屋發展實施自動化和機械化的潛力

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Investigating the Potential of Implementing Robotics and Automation in the Context of Large-scale Housing Development for Hong Kong

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Abstract: The construction industry in Hong Kong faces conspicuous challenges of high demands, safety, an ageing workforce, and stagnant productivity. Compared to the manufacturing industry, the degree of automation in the construction sector lags behind. Therefore, the consultancy project commissioned by the Construction Industry Council (CIC) in Hong Kong aimed to evaluate current on-site construction processes and to identify the existing bottlenecks that can be enhanced by implementing robotics and automation. In order to systematically execute the consultancy project, the project was carried in stages following a systems development approach in which key elements and requirements are systematically detailed and implemented. This report summarizes the key activities carried out and the results produced. Firstly, the outcomes of an analysis of background, situation, and requirements are outlined. Secondly, the outcomes of the identification process of priority areas for the use of on-site robots (including the definition of basic scenarios, an online survey carried, an on-site case study identifying and analyzing construction processes potentially suitable for robotics use, co-creation workshops to detail requirements and functions of potential robotic solutions, and the analysis of potential priority areas) is presented. Thirdly, the outcomes of an exemplary, technical detailing of the priority area "façade-processing" and the development of a prototype (mock-up) for demonstration and exhibition of the concept at CITAC are shown. Fourthly, the outcomes of the development of recommendations (with regard to process information modeling and business strategy) that flank the exemplarily detailed priority area are summarized. Lastly, the results of the development of a roadmap for robot technology development covering a 10-year time span and a draft proposal for a follow-up project are presented, which would focus on the development of a marketable version of the presented robot prototype by a Hong Kong and Shenzhen based consortium (that would resemble a robot supply infrastructure).

Acknowledgements

Contributors	Contribution
Construction Industry Council Hong Kong	Support with the carrying out of specific activities in Hong Kong, such as the organization of the various workshops, final demonstration at CITAC, etc. Provision of information about housing construction industry and case studies; facilitation of practical alignment of the study and a smooth progress of the activities carried out; facilitation of visits to Hong Kong Institute of Construction.
Hip Hing Engineering Co., Ltd	Organization of an extended site visit and on-site stay (4 weeks) to analyze construction processes in housing construction
Participants of on-line survey (April/May 2017) conducted among potential stakeholders in Hong Kong	Contribution to pre-identification of priority areas
Participants of co-creation workshops (T and P sessions, August 2017) and requirements confirmation workshop (December 2018) targeting stakeholders in Hong Kong	Contribution to discussion of requirements and functions of on-site robot solutions
Yau Lee Construction Co., Ltd.	Organization of site visits
HERO GmbH	Support as sub-contractors with the building of the mock-up according to specifications provided by TUM
AHORNER, painting company	Consultancy with regard to various types of painting processes such as painting with airless guns
Dr. Groth (business model expert), C. Zhao (management expert), TUM	Support with the development of business strategy elements
K. Pawitza (scientific assistant), TUM	Support with mock-up detailing, CITAC demonstration scenario development.
A. Bittner (leader of prototyping workshop facility), TUM	Cost calculation for a fully functional 1:1 scale prototype; support with mock-up design and building

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Key expressions

Artificial intelligence (AI): The study of "intelligent agents", any device that perceives its environment and takes actions that maximize its chance of successfully achieving its goals.

Automated/Robotic On-site Factory: A structured factory or factory-like environment set up at the place of construction, allowing production and assembly operations to be executed in a highly systematic manner by, or through, the use of machines, automation and robot technology.

Business model: A business model describes the rationale of how an organization creates, delivers, and captures value, in economic, social, cultural or other contexts. The process of business-model construction forms a part of business strategy.

Building Information Modeling (BIM): A digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition.

Co-creation workshop: A management initiative or form of economic strategy that brings different parties together (for example, a company and a group of customers) in order to jointly produce a mutually valued outcome.

Degree of Freedom (DOF): In a serial kinematic system, each joint, in terms of motion, gives the system a DOF. At the same time, the type of joint restricts the motion to a rotation around a defined axis or a translation along a defined axis.

End-effector: In robotics, an end effector is the device at the end of a robotic arm, designed to interact with the environment. The exact nature of this device depends on the application of the robot.

Heating, ventilation, and air conditioning (HVAC): The technology of indoor and vehicular environmental comfort.

Industry Foundation Classes (IFC): A platform neutral, open file format specification to describe building and construction industry data, which is not controlled by a single vendor or group of vendors.

Likert scale: A Likert scale is a psychometric scale commonly involved in research that employs questionnaires. It is the most widely used approach to scaling responses in survey research. The format of a typical five-level Likert item, for example, could be: (1) strongly disagree, (2) disagree, (3) neutral, (4) agree, and (5) strongly agree.

Mock-up: In manufacturing and design, a mock-up is a scale or full-size model of a design or device, used for teaching, demonstration, design evaluation, promotion among other purposes. A mockup is a prototype if it provides at least part of the functionality of a system and enables testing of a design.

Process Information Modeling (PIM): A process-oriented, case-focused approach that provides detailed information about a specific task. It breaks down into smaller, manageable data and is distributed to the right stakeholder at the right time.

Plug-and-play (PnP): In computing, a plug-and-play device or computer bus, is one with a specification that facilitates the discovery of a hardware component in a system without the need for physical device configuration or user intervention in resolving resource conflicts. The term was expanded to a wide variety of applications where the same lack of user setup is applied.

Research and development (R&D): A series of innovative activities undertaken by corporations or governments in developing new services or products, or improving existing services or products.

Robot-oriented Design (ROD): The theory of building design that emphasizes the idea that before the final on-site construction process, all parameters shall be considered at the earlier design and production stages. In order to establish determined conditions for robotic on-site operations, the elements of building subsystems (e.g. building structure, component, assembly method, and equipment selection, etc.) need to be geometrically and physically well-defined in accordance with robots and automation.

Single-task Construction Robots (STCR): Systems that support workers on the construction site in executing one specific construction process or task (e.g., digging, concrete leveling, concrete smoothening, brickwork construction, logistics, and painting) or by completely substituting the physical activity of human workers necessary to perform this one process or task.

Spider chart: A graphical method of displaying multivariate data in the form of a two-dimensional chart of three or more quantitative variables represented on axes starting from the same point.

Technology Readiness Levels (TRL): A method of estimating technology maturity of Critical Technology Elements (CTE) of a program during the acquisition process. TRL are based on a scale from 1 to 9, where 9 represents the most mature technology.

Venture capital (VC): A type of private equity, a form of financing that is provided by firms or funds to small, early-stage, emerging firms that are considered to have high growth potential, or which demonstrated high growth (in terms of number of employees, annual revenue, or both).

Vertical Delivery System (VDS): A system that transports parts/components on the construction site from the ground (e.g. material handling yard) to the floor level where the components shall be assembled.

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1 Structure of this report

The consultancy project commissioned by the Construction Industry Council (CIC) in Hong Kong aimed at evaluating current on-site construction processes and to identify the existing bottlenecks that can be enhanced by implementing robotics and automation. In order to systematically execute the consultancy project, the project was carried in stages following a systems development approach in which key elements and requirements are systematically detailed and implemented.

This report summarizes the key activities carried out and the results produced. In order to systematically execute the consultancy project, the project was divided into nine stages using a scientific methodology developed by NASA (explained in detail in *Chapter 3*). In *Chapter 2*, the outcomes of an analysis of background, situation, and requirements of the project are outlined. In *Chapter 3*, the outcomes of the process of an identification of priority areas for the use of on-site robots is presented. This includes the definition of basic scenarios, an online survey carried, an on-site case study identifying and analyzing construction processes potentially suitable for robotics use, co-creation workshops to detail requirements and functions of potential robotic solutions, and the analysis of potential priority areas. In *Chapter 4*, the outcomes of an exemplary, technical detailing of the priority area “façade-processing” are demonstrated. In Chapter 5, the development of a prototype (mock-up) for demonstration and the exhibition concept at CITAC are reported. In *Chapter 6* and *7*, the outcomes of the development of recommendations (with regard to process information modeling and business strategy) that are related to the exemplarily detailed priority area are summarized. In *Chapter 8*, a roadmap for implementing robotics and automation technology in Hong Kong’s housing construction industry as well as a draft strategy for executing follow-up projects are presented. In addition, in *Chapter 9*, key results and conclusions of each chapter are summarized in order that the readers can quickly retrieve the key points in each chapter of the report.

2 Background, situation and requirements

This chapter provides a brief introduction to the history of construction robots, and analyzes the existing issues of Hong Kong housing construction industry and the potential implementation of automation and robotic technology in the construction sector. The proposed solution is to be tailor-made for the Hong Kong construction industry, yet it has wider audiences in anticipation for the industry sector to be reformed. For example, the future construction sector will expose a cross-disciplinary characteristic that many industries coexist and collaborate. In this sense, upgrading the performance of the construction industry not only has the positive implication within one industry but also it will grant much greater contribution to the prosperity development of Hong Kong. Based on the findings of this chapter, the project team is able to identify priority areas for on-site robotics applications in Hong Kong construction industry using a specific methodology in the next chapter.

2.1 Introduction

During the 1980's, the Japanese construction sector put huge investments into R&D for developing construction robots and automated construction sites. At the time, a shortage of skilled labor, as a result of ageing society, was a major concern in the Japanese construction industry **(Kangari & Miyatake, 1997)**. Single-Task Construction Robot (STCR) was developed to address this issue and to attract young workers to get involved in the industry. In general, STCR is designed to focus on executing one or several specific construction tasks in a dedicated working area. Due to the complexity of the construction project, STCR is very different from the robots in manufacturing in terms of the composition, kinematics, navigation, and function. STCR is normally tailor-made to suite all stakeholders' requirements, rather than simply integrated into the construction project **(Bock & Linner, Construction Robots, 2016)**.

To be able to successfully adopt STCR, it is crucial to follow the notion of Robot-oriented Design (ROD). The ROD concept was first conceptualized in 1988 by Thomas Bock and later served as the principle for automated construction and robot-based construction sites around the world. This concept emphasizes the idea that during final on-site construction processes, all design parameters should be considered at the earlier design and production stages. The building components will be designed to be easily handled by robots during the assembly phase. When developing robotic technology for the construction sector, it is far more diverse and complicated than the operation in manufacturing plants **(Bock & Linner, Robot-Oriented Design, 2015)**.

Nowadays, Hong Kong experiences a similar circumstance such as labor shortage, demographic changes, and the urge of increasing construction efficiency. By implementing robotics and automation, technologies might be able to tackle some of the aforementioned issues. However, modern buildings consist of many complex structures, layouts, and subsystems. In addition, the construction industry can be influenced by other attributes, for example, economy and policies, resulting in imposing huge constraints when applying robotic technologies in construction. Hence, in the early development phase, it is vital to be aware of key stakeholder's requirements, understand the existing construction operation, and analytically evaluate the construction process. This method helps the project team to enumerate the current demand, and distinguish the optimum strategy.

In principle, there are several hurdles or levels to achieve construction automation, which include standardization, semi-automation, and full automation. Standardization can be achieved through prefabrication, and the prefabrication rates in Hong Kong's public housing construction (PHC) projects are relatively high **(Jaillon & Poon, 2009)**. Prefabrication was introduced to the PHC projects in the mid-1980s in Hong Kong. Then, the Hong Kong Housing Authority (HKHA) promoted extensively the usage of prefabricated elements and standard reusable formwork in the public sector **(Chiang, Chan, & Lok, 2006)**. The majority of the contractors are able to achieve 6-day-per-floor working cycle, thanks to the standardization in design. Optimistically, due to a high degree of standardization in the PHC sector, Hong Kong has the potential and willingness to upgrade to the next level.

This chapter provides an overview of the three scenarios proposed by Technology University of Munich (TUM) and Construction Industry Council (CIC). The first scenario aims to demonstrate the potential of Single Task Construction Robots (STCR) or applications that were applied in the construction sector worldwide. The second scenario will be structured in the principle that integrated construction system and semiautomatic construction system will be used in the construction industry. The third scenario will illustrate the potential of applying fully automated construction system in Hong Kong. The selection of the technologies (e.g. STCR, integrated systems and fully automated construction systems) in the document are determined based on analysis of the CIC's labor shortage survey outcome, see *Figure 2-1* to *Figure* 2-4, as well as *Figure 2-5* that was exclusively provided as a case study example. In addition, the chapter illustrates a brief description of the selected systems, their operational process and the potential of promoting automation and robotic technology, in subcontractors, equipment manufacturers and the construction sector in Hong Kong. Furthermore, the first phase of the project will help the stakeholders to formulate short-term actions and long-term strategies in order to meet the future needs.

#	Trade	2018	2019	2020	2021	2022
1	Bar Bender & Fixer					
2	Concretor					
4	Plumber					
6	Scaffolder					
7	Carpenter					
9	Plant & Equipment Operator (Load Shifting)					
12	General Welder					
13	Metal Worker					

Figure 2-1: Forecast of Shortage of Skilled Construction Workers (Image: Construction Industry Council, 2018)

Figure 2-2: Forecast of shortage of skilled construction Workers. (Image: Construction Industry Council, 2018)

Figure 2-3 indicates the shortage of skill trades and the proposed practical robotic solutions that may potentially improve the situation. The analysis outcome is based on the analysis of the CIC's manpower forecast.

Skilled Workers shortage analysis	
Trade	**Proposed practical robotic solutions**
Carpenter (Wooden formwork, Joiner)	• Formwork system design • Self climbing formwork system • Logistic supply system for formwork • Exoskeleton
Plasterer Terrazzo & Granolithic worker (Plastering/ interior finish), Plastering or rendering/ exterior), Stone work, stonemason work)	• Plastering machine • Exterior rendering/ painting machine • Vertical material transportation system • Exoskeleton
Refrigeration/ AC/Ventilation Mechanic (Assembly, Inspection, Transportation, Maintenance)	• Off-site prefabrication • Logistic supply system (on-site and off-site) • On-site workshop/ factory • Exoskeleton

Figure 2-3: Skilled workers shortage analysis (Image: TUM, 2017.)

The *Figure 2-4* indicates the analysis of the case study construction project. The proposed practical robotic solutions will assist the related construction trade.

Figure 2-4: Construction trade project analysis based on the case study (Image: TUM, 2017)

Figure 2-5 demonstrates the 6-Days construction cycle of the selected case study building.

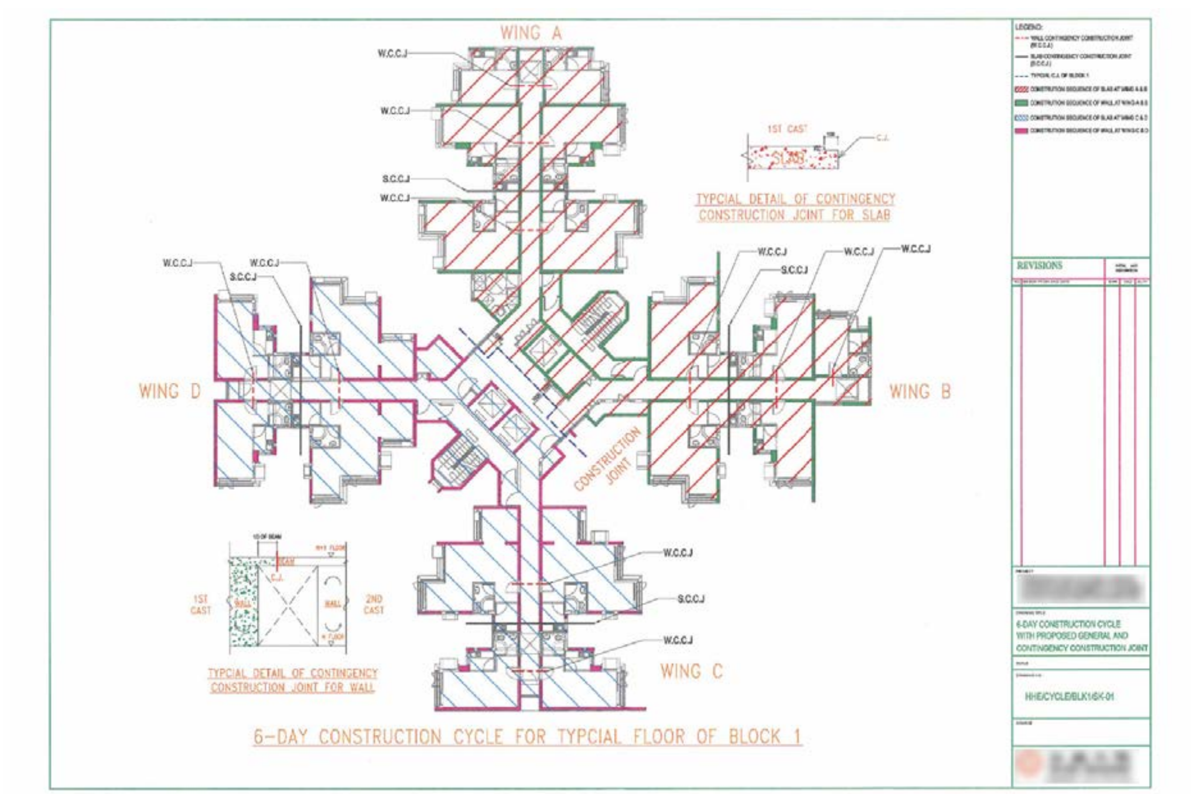


Figure 2-5: 6-Days construction cycle of the typical floor in the case study project

2.2 Task summary

The current consulting study is investigating the potentials of automation and robotics in the context of large-scale housing industrialization for Hong Kong with the goal of transforming Hong Kong's construction industry into a high-tech sector in the end. The study will specifically identify, select, and detail "practical" solutions for the utilization of automation and robotics in the construction of public high-rise housing.

2.2.1 General situation of public housing in Hong Kong

- One third of Hong Kong population are housed in public housing blocks.
- Public housing has a long history in Hong Kong dating back to the 1960s.
- Application for the allocation to a public housing is around 5 years on average.
- Floor plans and flat sizes are optimized/minimized: 25-35 square meter for flat for two adults.
- Big pressure to build new public housing fast.
- Around one-third pre-cast concrete elements in terms of volume are delivered from mainland China.
- High-rise typology with (nearly) symmetric wings is usual with up to 47 floors for public housing standard in Hong Kong nowadays. Long history/experience/evolution of floor plan design. Highly standardized floor plans.
- In the past 4-5-day cycles used; now shift back to six-day cycles due to safety and quality reasons.
- Standardized aluminum windows frames are used for public housing.
- The ventilators/coolers in front of the windows are under responsibility of the renter, only installation place is provided.
- Design is adjusted /optimized according to crane reach area and the requirement of symmetry for formwork circulation.
- Public housing development now can be single or double blocks due to limited land supply in Hong Kong.

2.2.2 Clarifications of study scope

- This project shall focus on public housing high-rise construction.
- Focus on aboveground construction.
- The largest drivers for automation in Public Rental Housing (PRH) are:
    a. Safety concerns,
    b. Labor shortage in creating trades/professions,
    c. Time (public housing needs to be supplied fast),
    d. Cost (public housing should be affordable)
    e. Quality (recent incidents with lead pollution in drinking water).
- Study of automation potentials will be based on an exemplary/characteristic development area/case.
- The study will also consider additional data provided by the CIC, such as:
    a. Work, safety, and building regulations (e.g. to what extent is work at night, etc. allowed)
    b. Analysis of manpower shortage
    c. General Information about stakeholder, value creation models, etc.

2.3 Conclusions

Key insights and outcomes with regard to background, situation, and requirements in this chapter:

1. A brief introduction to the history of construction robots is provided.

2. The existing issues of Hong Kong housing construction industry are analyzed.
3. The potential implementation of automation and robotic technology in the construction sector is described.
4. The study scopes of this consultancy that were agreed by CIC and TUM are clarified.

3 Identification of the priority areas for on-site robot applications in Hong Kong's public housing construction industry

The main goal of this chapter is to identify priority areas for on-site robotics applications in Hong Kong construction industry using a specific methodology. Based on the results of this chapter, the project team is able to specify the details of the identified priority areas for on-site robotics applications in the next chapter. In order to systematically execute the consultancy project, the project was divided into nine stages; see *Figure 3-1* **(National Aeronautics and Space Administration, 2007)**.

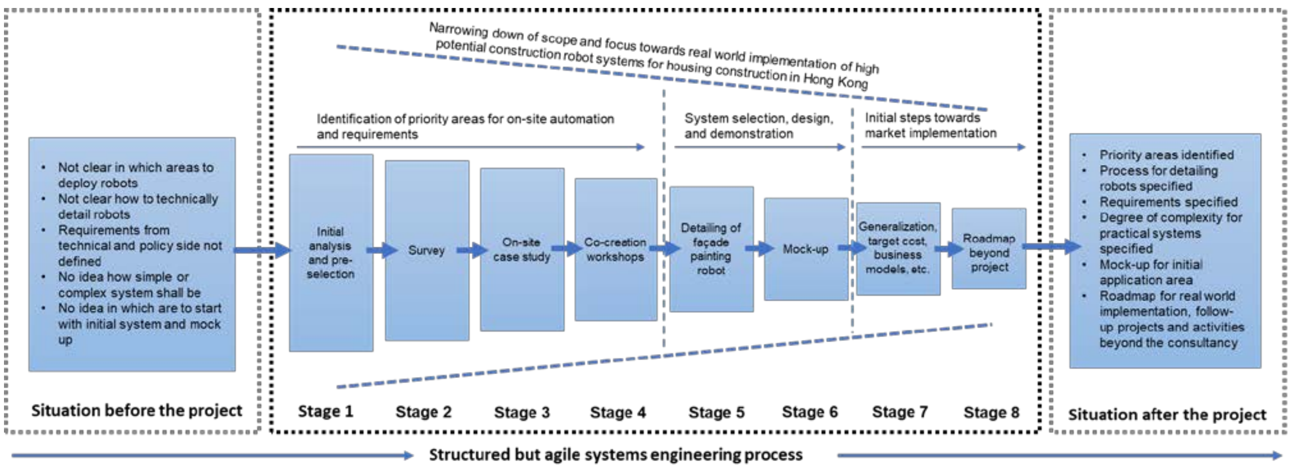


Figure 3-1: Method used in the consultancy study (adapted from NASA Systems Engineering Process)

As shown in the figure above, the first stage includes initial research, literature review, preselection of the proposed robotics and automation strategies, and proposal case scenarios. The second stage comprises online surveys. The third stage is on-site case study. The fourth stage is co-creation workshops. The fifth stage works on the concept development, detailing and finalization of the selected system. The sixth stage includes a final demonstration of the system, construction of the demonstration mock-up, and validation of the design concept. The seventh stage includes generalization, target cost, and the business model. The eighth stage includes planning for future work, as well as recommendations for future development. This chapter will methodically illustrate from stage 1 to stage 4 of the project and explore how to use applied research strategies in an early stage decision-making procedure, when conducting this type of industry-related and technology-focused consultancy project.

3.1 Pre-identification of potential scenarios and technologies

Based on the findings from the background studies stated in the previous chapter and internal discussions between TUM, CIC and key stakeholders, there were 17 robotic and automation systems proposed (Bock & Linner, Construction Robots, 2016). The selected systems were also systematically distributed into three use case scenarios. The scenarios were analyzed based on the evolution of degree of automation, and their ability to be integrated into industry during the course of the proposed development roadmap.
Scenario 1 (see *Figure 3-2*) aims to demonstrate the potential of single task construction robots (STCR) to assist profession-specific, physically demanding and repetitive tasks on-

site. Under this scenario, there are limited alterations, which the existing building has to adopt. There is modest impact on the conventional construction industry and the structural performance of the building. It also serves as the backbone for the future development.

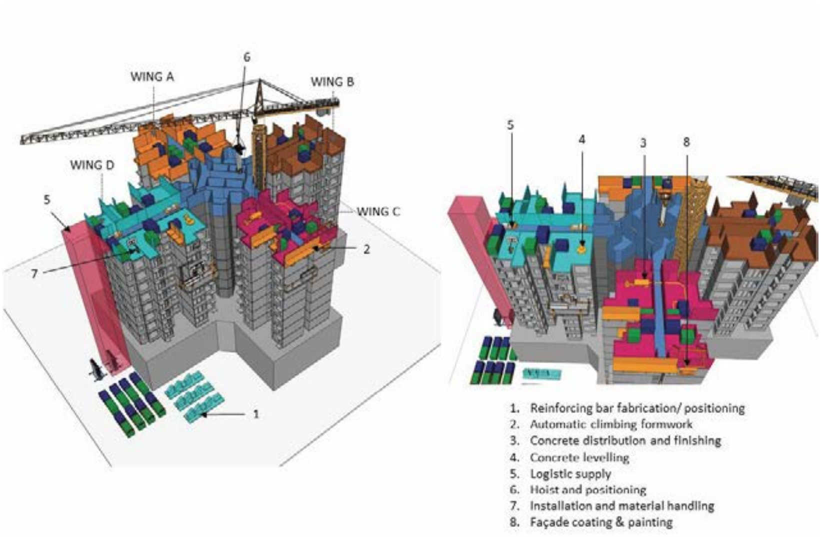


Figure 3-2: Brief description of scenario 1 (Image: TUM, 2017)

Scenario 2 (see *Figure 3-3*) integrates automatic and semiautomatic construction systems. In this scenario, some of the proposed solutions may require alteration of the existing building design. For instance, a higher degree of prefabrication rate is recommended **(Bock & Linner, Robotic Industrialization, 2015)**. The building method may need to adopt the use of robotics and automation.

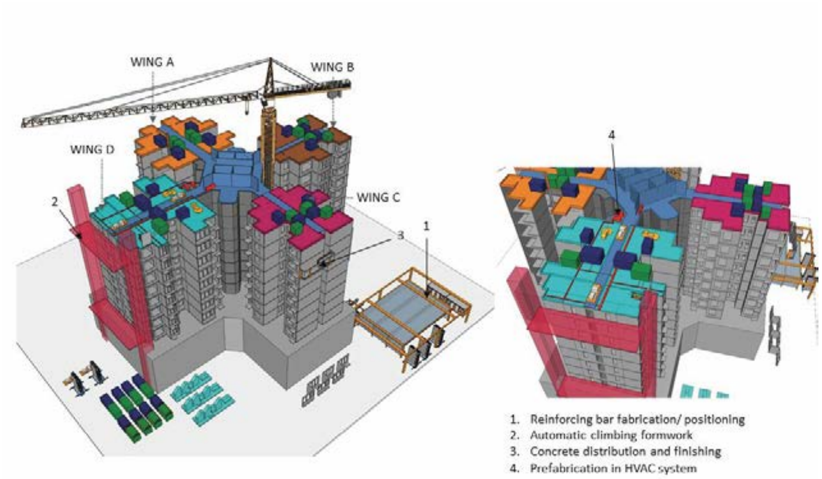


Figure 3-3: Brief description of scenario 2 (Image: TUM, 2017)

Scenario 3 (see *Figure 3-4*) illustrates the potential of applying a fully automated construction system in Hong Kong. In this scenario, the proposed solution can be applied only if the building is designed in consideration of ROD. This scenario describes the ultimate goal that can be achieved when applying feasible automation and robotics technologies in the construction industry in Hong Kong. The scenarios also functioned as project use cases that allow the stakeholder analysis to be conducted.

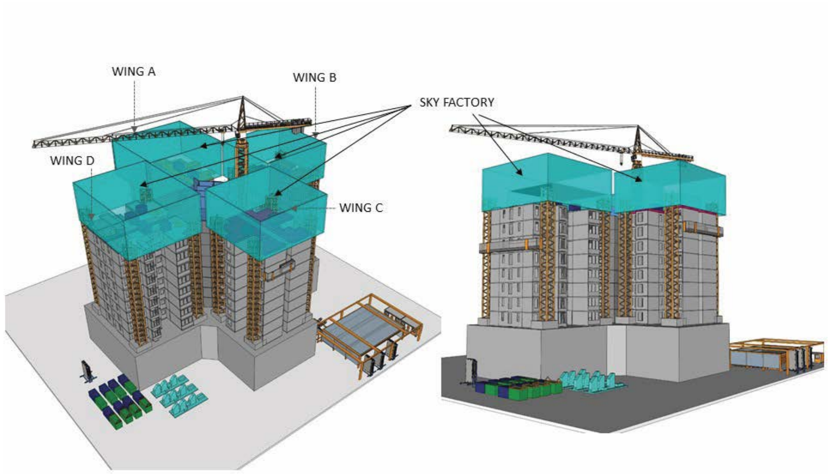


Figure 3-4: Brief description of scenario 3 (Image: TUM, 2017)

A value matrix (see *Figure 3-5*) is dedicated to the proposed systems under each scenario to classify the functional and non-functional requirements. For example, in this case, the functional requirements specify the technical specification of the system, the compatibility, the productivity, and the Technology Readiness Level (TRL). The non-functional requirements express the non-measurable function or quality of the system, the governmental policies and regulations, the legal matter, feasibility, and sustainability. The value matrix of the proposed systems was distributed out to the selected stakeholders and was scored with a value that measures those requirements fulfilling the stakeholders' expectations. It also provides the background information for the online survey in the later stage of the project.

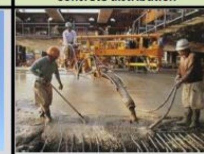
Performance indicators					
			System 1	System 2	System 3
			Reinforcing bar fabrication/ positioning	Automatic climbing formwork	Concrete distribution
					
Aim					
	1.1 Technological specification				
		Size & weight	1-5 ( )	1-5 ( )	1-5 ( )
		Usability	1-5 ( )	1-5 ( )	1-5 ( )
		Technical suitability (e.g.payload)	1-5 ( )	1-5 ( )	1-5 ( )
	1.2 Compatibility				
		Compatible with existing machinery	1-5 ( )	1-5 ( )	1-5 ( )
		Delivery and logistics	1-5 ( )	1-5 ( )	1-5 ( )
		Compatible with building structure	1-5 ( )	1-5 ( )	1-5 ( )
	1.3 Productivity				
		Reduce personal month (PM)	1-5 ( )	1-5 ( )	1-5 ( )
		Speed up construction	1-5 ( )	1-5 ( )	1-5 ( )
		Increase construction quality	1-5 ( )	1-5 ( )	1-5 ( )
		Improve construction safety	1-5 ( )	1-5 ( )	1-5 ( )
		Eliminate the "3Ds" (Dirty, Dangerous, Demeaning)	1-5 ( )	1-5 ( )	1-5 ( )
		Production cost saving	1-5 ( )	1-5 ( )	1-5 ( )
	1.3 TRL & Production				
		Implementation feasibility	1-5 ( )	1-5 ( )	1-5 ( )
		Off the shelf product	1-5 ( )	1-5 ( )	1-5 ( )
		Prototype realizability	1-5 ( )	1-5 ( )	1-5 ( )
		Development cost (R&D)	1-5 ( )	1-5 ( )	1-5 ( )
		Future commercial potential	1-5 ( )	1-5 ( )	1-5 ( )
		Easy to outsource the production	1-5 ( )	1-5 ( )	1-5 ( )
	1.4 Safety operation				
		Operational Safety & Risk	1-5 ( )	1-5 ( )	1-5 ( )
	1.6 Sustainability			1-5 ( )	1-5 ( )
		Operational and environmental	1-5 ( )	1-5 ( )	1-5 ( )
		Embedded energy	1-5 ( )	1-5 ( )	1-5 ( )
		Maintenance	1-5 ( )	1-5 ( )	1-5 ( )
		Reuse & upgrade	1-5 ( )	1-5 ( )	1-5 ( )
	1.7 Others				
		Cultural acceptance	1-5 ( )	1-5 ( )	1-5 ( )
		Cross disciplinary collaboration	1-5 ( )	1-5 ( )	1-5 ( )
		Traning and fulfill technologies gaps	1-5 ( )	1-5 ( )	1-5 ( )
		Legal requirements	1-5 ( )	1-5 ( )	1-5 ( )

Figure 3-5: Value matrix of the proposed systems in each scenario and its partial enlargement (Image: TUM. 2017)

3.1.1 Scenario 1

The first scenario focuses on the deployment of STCRs in the construction field. As we know, "dirty, dangerous and demeaning" (also known as 3Ds) is often associate with the construction sector. This also reflects the phenomenon of the current construction industry in Hong Kong. The construction industry in Hong Kong faces many challenges, namely; lack of urban development land, lack of skilled labor (demographic changes), and inefficiency of the industry to cope with the increasing demand. Integration of the STCRs technology will potentially improve the overall performance of the construction industry. STCRs are systems that support workers on the construction site in executing one specific construction task or process (e.g., digging, concrete leveling, formwork assembly, painting, logistic and so on), or by completely substituting the physical activity of human labor necessary to perform this one process or task. The processes and tasks assisted or fully executed by STCRs are in most cases relatively physically demanding, repetitive and craft specific.

There are nine systems proposed by the project team from TUM after conducting detailed analysis on the demand/supply trend of the skilled labor and the construction method that deployed in Hong Kong (see *Figure 3-6*). For a detailed description and analysis of each technology in Scenario 1, please refer to *Appendix 1*.

Figure 3-6: Pre-selected robot systems in Scenario 1

3.1.2 Scenario 2

The second scenario will be focused on the principle that integrated construction system and semiautomatic construction system will be used in the construction industry. This scenario is representing the phase in between the STCRs and the deployment of the fully automated application. The disadvantages of the STCRs include, low adaptability, high initial investment and long setup time on the construction site. The goal of the second scenario is to provide a range of integrated system concepts that will increase the productivity yet adaptable, flexible and able to execute multiple work tasks.

There are five systems proposed by the project team from TUM after conducting detailed analysis on the demand/ supply trend of the skilled labor and the construction method that can be deployed in Hong Kong (see *Figure 3-7*). For a detailed description and analysis of each technology in Scenario 2, please refer to *Appendix 2*.

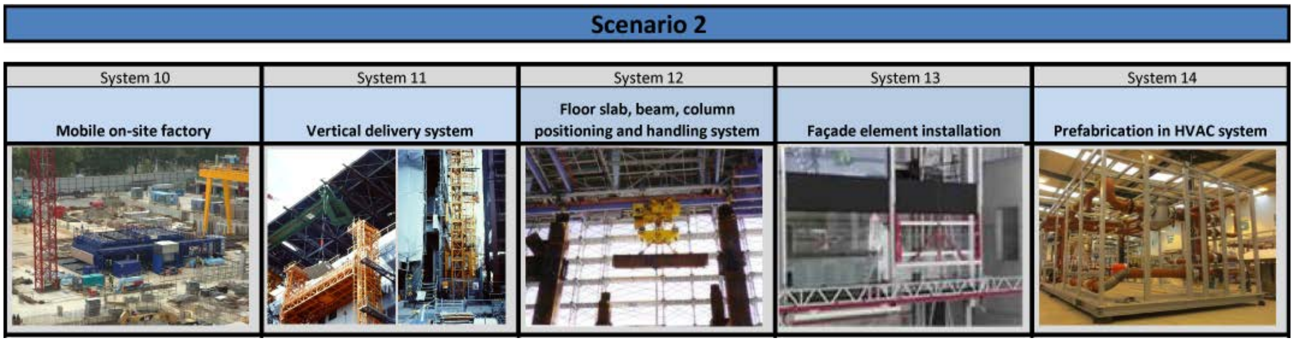


Figure 3-7: Pre-selected robot systems in Scenario 2

3.1.3 Scenario 3

The third scenario will be focused on the implementation of highly automated construction system and on-site factory. It is important that the construction industry to be aware of the technological breakthrough form the other industrial sectors, as well as the worldwide development in construction on-site automation technology. The main concept of setting up automated on-site factories was to integrate stand-alone or single-task construction robot (STCR) technology in structured on-site environments into networked machine systems. In return, this would improve the organization, integration, and material flow on the construction site (apart from the possibility to off-site manufacture) through interlinked machine activities. The Hong Kong construction industry will be inspired by the examples provided in this document while further develop concept, which based on industrialized, automated, and production line–like factory processes on the construction site **(Bock & Linner, Site automation, 2016)**.

There are three concepts proposed by the project team from TUM after conducting detailed analysis on the demand / supply trend of the skilled labor and the construction method that deployed in Hong Kong (see *Figure 3-8*). For a detailed description and analysis of each technology in Scenario 3, please refer to *Appendix 3*.

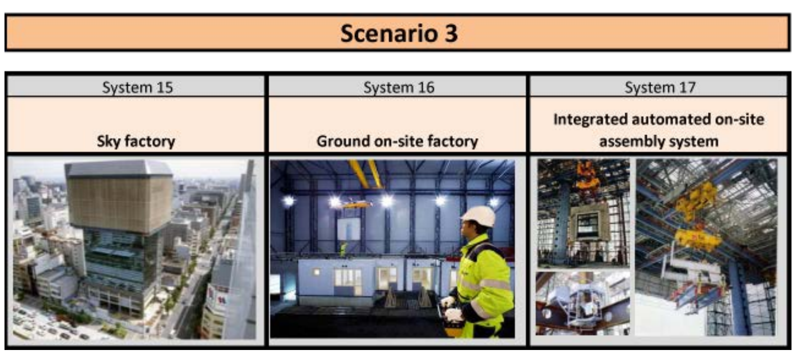
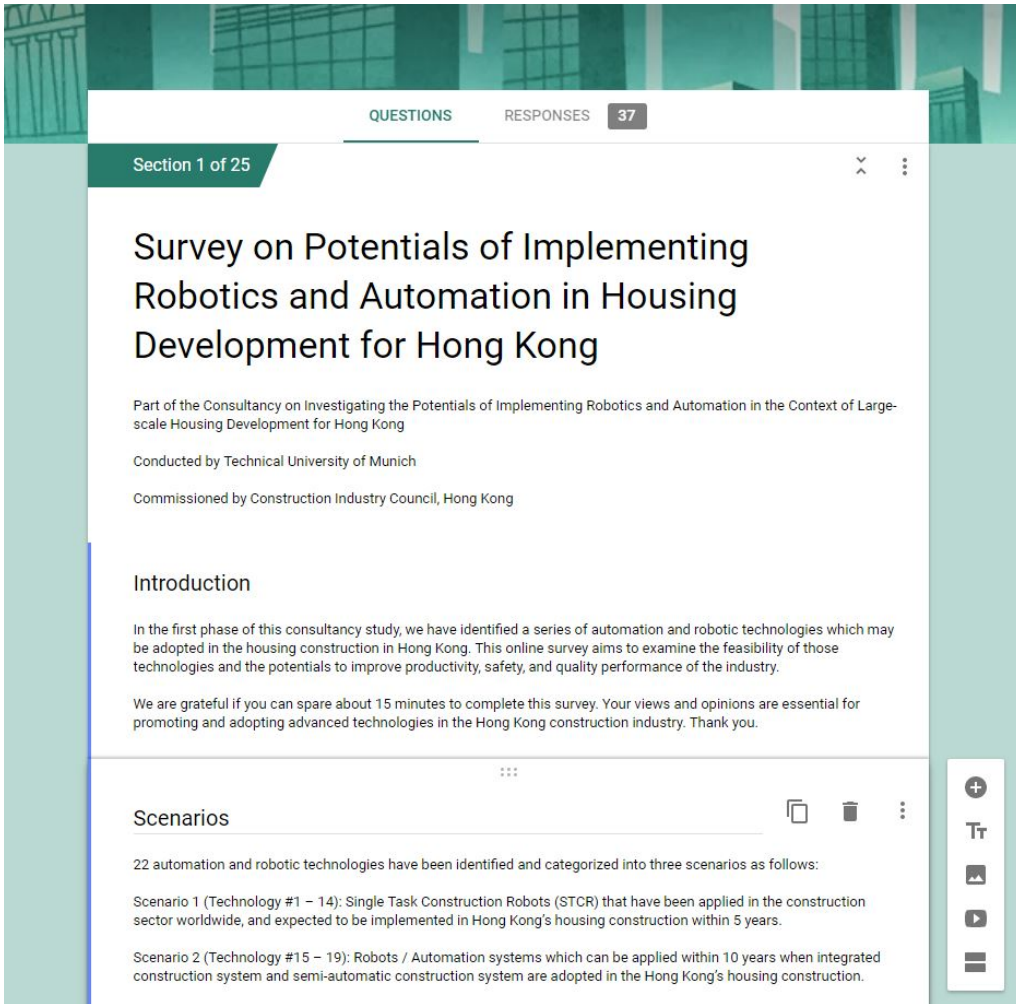


Figure 3-8: Pre-selected robot systems in Scenario 3

3.2 Online survey (selection of suitable approaches by industry experts and practitioners)

In the first stage of this consultancy study, TUM has identified a series of automation and robotic technologies, which were proposed to PHC. In order to examine the feasibility of these automation and robotic technologies, as well as their potentials to improve productivity, safety, and quality of the industry to Hong Kong industry, an online survey (powered by Google Forms, see *Figure 3-9*) was conducted, and its methodology and results are described as follows.


QUESTIONS RESPONSES 37

Section 1 of 25

Survey on Potentials of Implementing Robotics and Automation in Housing Development for Hong Kong

Part of the Consultancy on Investigating the Potentials of Implementing Robotics and Automation in the Context of Large-scale Housing Development for Hong Kong

Conducted by Technical University of Munich

Commissioned by Construction Industry Council, Hong Kong

Introduction

In the first phase of this consultancy study, we have identified a series of automation and robotic technologies which may be adopted in the housing construction in Hong Kong. This online survey aims to examine the feasibility of those technologies and the potentials to improve productivity, safety, and quality performance of the industry.

We are grateful if you can spare about 15 minutes to complete this survey. Your views and opinions are essential for promoting and adopting advanced technologies in the Hong Kong construction industry. Thank you.

Scenarios

22 automation and robotic technologies have been identified and categorized into three scenarios as follows:

Scenario 1 (Technology #1 – 14): Single Task Construction Robots (STCR) that have been applied in the construction sector worldwide, and expected to be implemented in Hong Kong's housing construction within 5 years.

Scenario 2 (Technology #15 – 19): Robots / Automation systems which can be applied within 10 years when integrated construction system and semi-automatic construction system are adopted in the Hong Kong's housing construction.

Figure 3-9: Screenshot of the online survey

3.2.1 Survey methodology

The aforementioned pre-selected robotic systems in three scenarios plus 5 additional construction robotic technologies suggested by CIC, namely interior painting, interior wall plastering, automated bricklaying, automated interior tiling, and robotic marking in Scenario 1 are listed in the questionnaire and these systems' technical details are described in the questionnaire. Specifically, the proposed technologies in the online survey include: T1 reinforcing bar fabrication positioning; T2 automatic climbing formwork; T3 concrete distribution; T4 concrete leveling and finishing; T5 logistics supply; T6 hoist and positioning; T7 installation and material handling; T8 façade cleaning and exterior finishing; T9 interior painting; T10 interior wall plastering; T11 automated bricklaying; T12 automated interior tiling; T13 robotic marking; T14 exoskeleton; T15 mobile on-site factory; T16 vertical delivery system; T17 building components positioning and handling; T18 façade element installation; T19 prefabrication in HVAC system; T20 sky factory; T21 ground on-site factory; and T22 integrated on-site assembling system (see *Figure 3-10*).

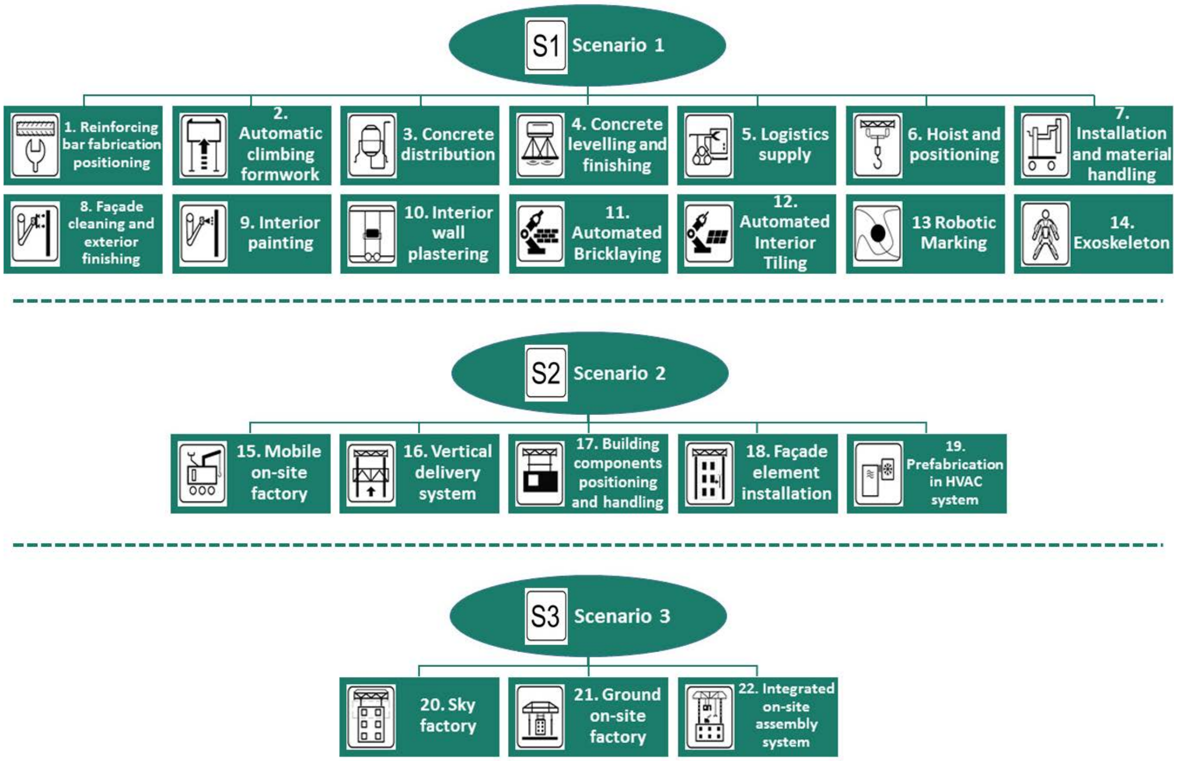


Figure 3-10: 22 selected construction automation and robotics systems in 3 scenarios for online survey

The survey follows a two-round selection method **(Nanyam, Basu, Sawhney, & Prasad, 2015)**, see *Figure 3-11*. The first round is to examine these proposed systems' feasibility for the PHC in Hong Kong (the primary attribute). Once accepted, all attributes (e.g., feasibility, improvement of productivity, safety, and quality) of these systems are further evaluated. Each question is based on the Likert Scale **(Likert, 1932)**. In addition, survey participants can leave comments to each technology.

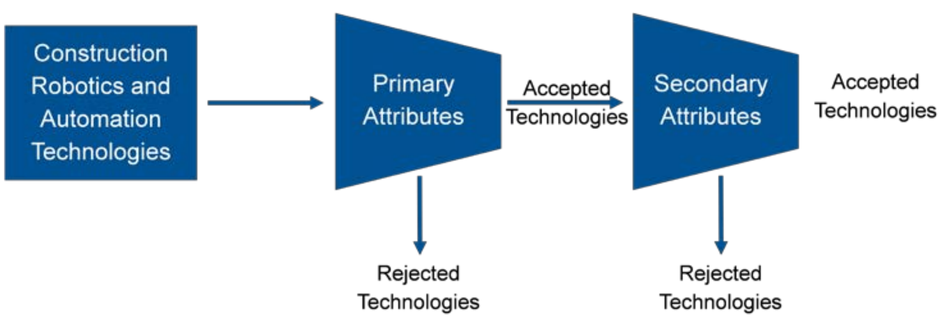


Figure 3-11: Survey selection method

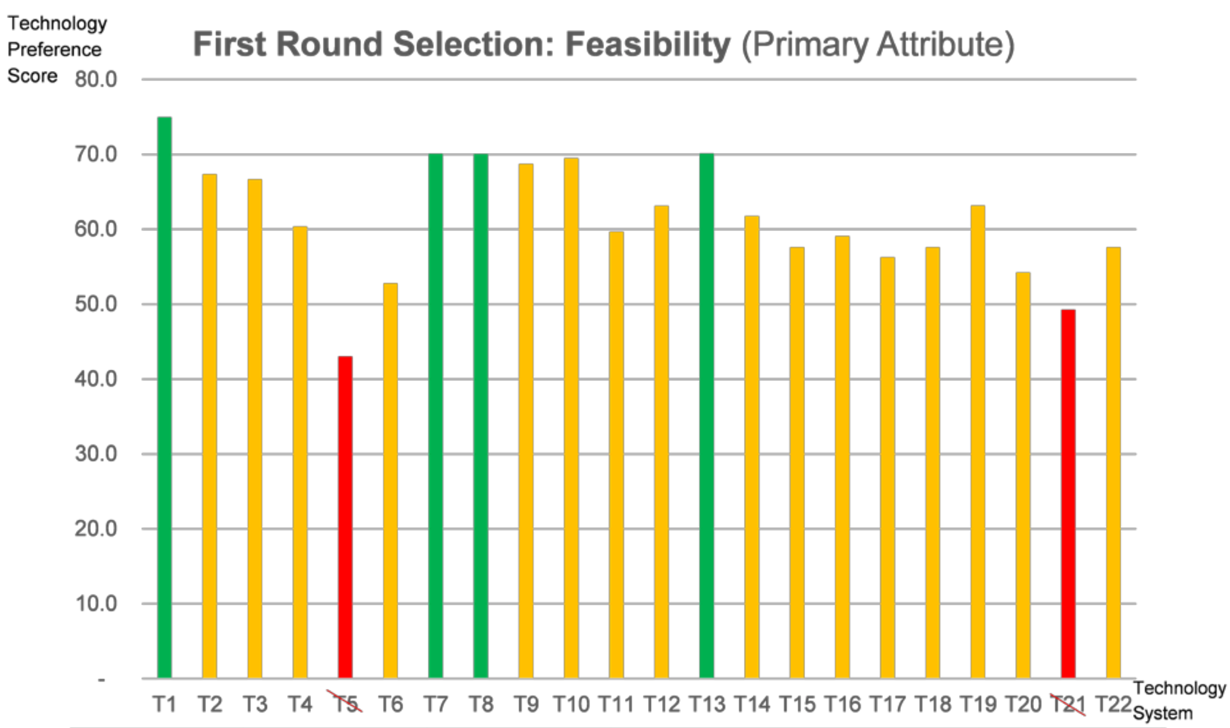
This is the equation followed for calculating the TPS of the attributes of each technology:

$$\text{TPS} = \sum_{i=1}^{5} Pi \times Wi \qquad (1)$$

- TPS = Technology Preference Score
- P = Percentage of Preference
- W = Weighted Value (strongly agree=100; agree=75; neutral=50; disagree =25; strongly disagree=0)
- i = Likert Scale

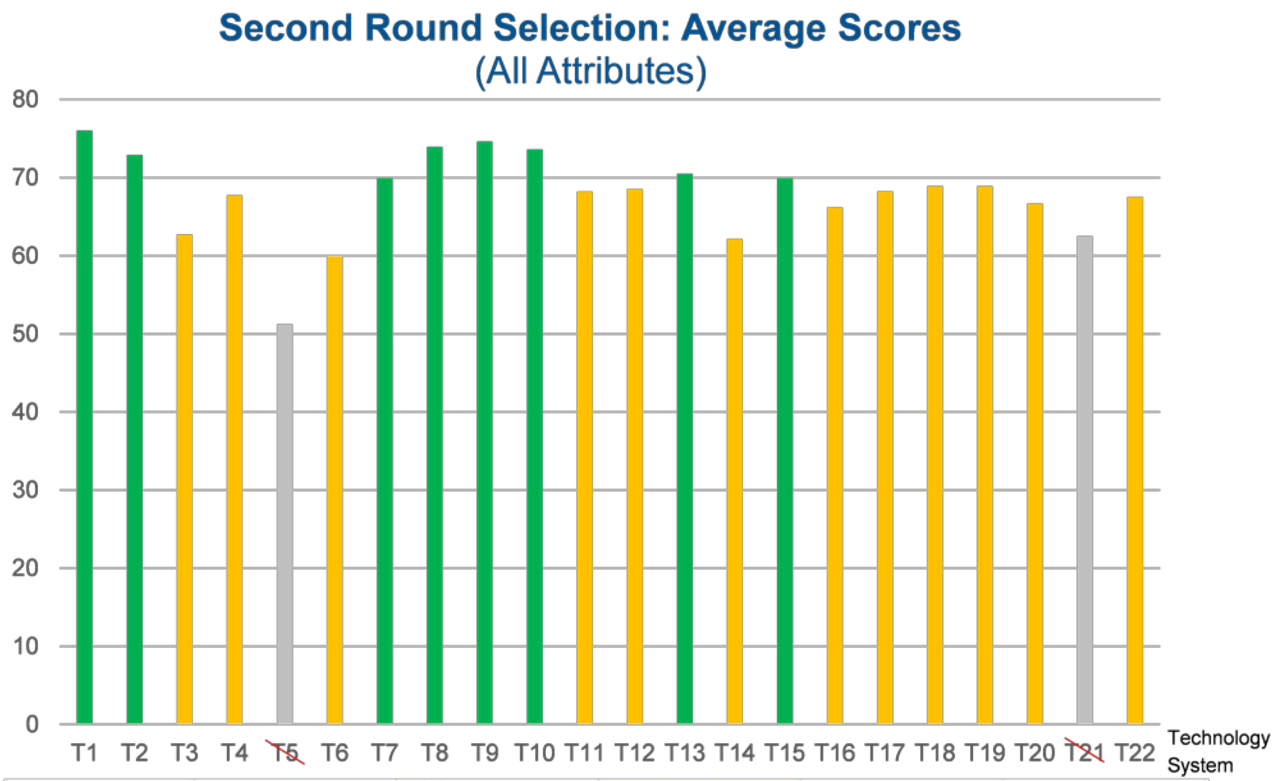
3.2.2 Survey results

The online survey was sent out to more than 200 professionals/stakeholders from the Hong Kong construction industry, and 36 effective survey responses were received. Professionals are from various backgrounds: 36% of the participants are contractors, 28% are consultants, 14% are clients, 14% are policymakers, 5% are academics, and 3% are NGO members. 82.4% participants have more than 10 years of experience in the construction industry. After calculating the survey data according to the aforementioned method, the survey results of the two-round selection are listed as below (see *Figure 3-12* and *Figure 3-13*). The first round selection is to examine the feasibility as the primary attribute. The second round selection is to examine the average scores of all attributes including feasibility as the primary attribute, and improvement of productivity, and safety, building quality as the secondary attributes. Technologies with a score above 70 are strongly recommended; between 50 and 70 are recommended; below 50 are poorly or not recommended. Logistics supply and ground on-site factory are neglected visually by a red slash in the first-round feasibility examination according to the criteria (as their feasibility scores are under 50).



	Strongly recommend	Highly recommend	Recommend	Poorly recommend	Not recommend
Result criteria	X ≥ 90	70 ≤ X < 90	50 ≤ X < 70	30 ≤ X < 50	X ≤ 30

Figure 3-12: Survey scores of the first round selection



	Strongly recommend	Highly recommend	Recommend	Poorly recommend	Not recommend
Result criteria	X ≥ 90	70 ≤ X < 90	50 ≤ X < 70	30 ≤ X < 50	X ≤ 30

Figure 3-13: Survey scores of the second round selection

In conclusion, the result of the two-round selection summarized in *Table 3-1* shows that in Hong Kong, the construction robotics and automation technologies are overall approved by the local professionals and stakeholders. The highly recommended technologies are of high priority, and thus can be implemented in the near future. The recommended technologies are also demanded, but there is a long way to go before they can be fully implemented. However, due to the actual situation in Hong Kong, some technologies are not practical at the moment, such as T5 logistic supply and T21 ground on-site factory.

Table 3-1: Final survey results

Highly Recommended Technologies	T1 (Reinforcing Bar Fabrication/ Positioning) T2 (Automatic Climbing Formwork) T7 (Installation and Material Handling) T8 (Façade Coating, Painting, Cleaning and Exterior Finishing) T9 (Interior Painting Application) T10 (Interior Plastering Application) T13 (Robotic Marking) T15 (Mobile On-site Factory)
Recommended Technologies	T3 (Concrete Distribution) T4 (Concrete Leveling and Finishing) T6 (Hoist and Positioning) T11 (Automated Bricklaying) T12 (Automated Interior Tiling) T14 (Exoskeleton) T16 (Vertical Delivery System) T17 (Floor Slab, Beam, Column Positioning and Handling System) T18 (Facade Element Installation) T19 (Prefabrication in HVAC System) T20 (Sky Factory) T22 (Integrated & Automated On-site Assembly System)
Rejected Technologies	T5 (Logistics Supply) T21 (Ground On-site Factory)

3.3 On-site case study of a Hong Kong housing construction project (identification and analysis of construction processes suitable for robot use)

Shortly after the online survey, the TUM project team travelled to Hong Kong to conduct a comprehensive on-site case study, which was organized by CIC and a local main contractor. The project consists of two residential building blocks (one 14-storey and the other 16-storey) both buildings are designed as Home Ownership Scheme project (see *Figure 3-14* and *Figure 3-15*). Since the case study buildings were close to the completion stage, limited site activities could be observed. The research team was able to access the site diary and the construction imagery folder, which documents the entire construction sequence to date. The main objectives of the on-site study are as follow:

- To understand current workflow, techniques, regulations, and tenders process of the PHC.
- To identify the Key Performance Indicator (KPI) that measures construction success of the project.
- To discuss and exchange ideas with the site manager, skilled workers, and contractors in regards to the implementation of construction robotics in Hong Kong.
- To determine which working process is worth automating.
- To map out feasible concepts and roadmaps for the future development.

First, a brief tour around the construction site was conducted supervised by the site manager. During the tour, job site layout, composition of the construction crews, health and safety measures, and recycling facilities were demonstrated and explained in detail. In general, the site and work tasks were well organized and planned in a conventional manner. The construction strictly followed a 7-8 days cycle; this is due to the remote location of the site to the Hong Kong main islands. The site is very congested; there is limited space that can be used for material storage and vehicle maneuvering.

Figure 3-14: Site photos

Figure 3-15: Interior view of the site

Extensive interviews were conducted between the TUM project team and the site manager, engineers, workers, and contractors. The purpose of the interview is to understand the current workflow, constraints and whether it can be improved by implementing automation or robotics. The selections were made under the following considerations: 1) if the on-site task is repetitive and/or labor intensive; 2) if the task subject to human error; 3) if the task is costly both finically and physically; 4) if the task subject to the skilled labor shortage; 5) and if the task imposes significant safety hazards. The detailed results of the investigation can be seen in *Table 3-2*:

Table 3-2: Detailed results of the on-site investigation

On-site task discussed	Opportunities when it is automated	Main constrains for automation	Potential to be automated
Reinforcing Bar Fabrication/ Positioning	Improve productivity, quality of work	Lack of space on-site, Research investment	Low
Formwork installation	Increase speed, improve safety	Lack of space on-site , Research investment, difficult to validate	Medium
Logistic supply	Improve productivity, safety	Lack of space on-site, heavily rely on suppliers, cost	Low
Hoist, positioning	Increase speed, improve safety	Difficult to validate, the existing method is very mature and fast, cost	Medium
Material handling	Improve productivity, safety	Difficult to validate, lack of infrastructure, the existing building is not adequate to support the additional weight, cost	Low
Façade work	Improve productivity, quality of work, safety	Research investment	High
Interior painting	Improve productivity, quality of work	Research investment	High
Interior plastering	Improve productivity, quality of work	Research investment	High
Interior tilling	Improve productivity, quality of work	Limited space where requires tilling application	Low
Marking	Improve productivity	Difficult to maneuver & navigate, Research investment	Low
Exoskeleton	Improve productivity, safety	Research investment, acceptability	Low
Mobile on-site factory	Improve productivity	Lack of space on-site, Research investment	Low
Vertical delivery system	Improve productivity, safety	Research investment, the existing method is mature	Low

There are few on-site tasks that were investigated extensively, in which five of them were considered worth automating. They include; formwork installation, hoisting and positioning, façade work, interior painting, interior plastering, in which the façade work (see *Figure 3-16*), interior painting, and interior plastering have the higher potential to be automated.

Figure 3-16: Exterior painting application

The objective of the next stage is to analyze these three tasks in detail. The detailed workflow, work method, amount of involved labor, time, and cost needed for the task were investigated.

(1) The existing methods for exterior façade coating and painting are described as below:

<u>Surface requirement:</u>

- Coating works will be carried out under suitable conditions of weather, temperature, humidity, ventilation and illumination at all stages to ensure quality can be maintained.
- Ensure a suitable condition for coating. All surfaces are dry. Substrate moisture content is to be 15% or below and Protimeter can be used for moisture measurements.
- Regard environmental conditions: Coating should not be applied in temperatures below 10 °C and when the Relative Humidity exceeds 90%.

<u>After the exterior façade is well prepared, three layers of coating will be applied. The specifications of the three coatings are (see detail in *Table 3-3*):</u>

a. Primer Coat (Water-Based Primer Coat): Apply one coat to the whole surface by roller/ brush/ spray.
    - Consumption: 0.15kg / m^2/ coat
    - Interval Curing: Over 2 hours
    - Mixing Ratio: Biofine Sealer/ clean water, -20 ltr / 5% by weight
b. Texture Coat (Water-Based Acrylic Resin Texture Coat): Apply one coat to the whole surface by spray.
    - Consumption: 0.45kg / m^2/ coat (fine texture), 0.85kg/ m^2/ Coat (medium texture)
    - Interval Curing: Over 24 hours
    - Mixing Ratio: Lena Luck/ Clean water, -26 kg/ 2 -5% by weight
c. Top Coat (Water-Based Acrylic Resin Color Protective Top Coat): Apply two coats of "Acristar Century" to the whole surface by roller/brush/spray.

- Consumption: 0.15kg / m^2/ coat
- Interval Curing: Over 2 hours
- Final Curing: Over 24 hours
- Mixing Ratio: Acristar Century/ Clean water -20 ltr/ 5% by weight

Tools and equipment required for the task:

- Suspended working platform (Gondola)
- AMAX low noise air compressor 3.0HP/ 50L (or similar)
- Air paint spray gun
- Paint bucket
- Dust Brush & metal wire brush

Table 3-3: Task analysis of façade coating

Task	Labor	Time	Cost
Installation of the Gondolas X 40	3 workers	2 weeks	1000 HK$ per labor per day
Cleaning and preparation of the external wall, skim coating of the wall	3 workers	Up to 4 weeks	1000 HK$ per labor per day
Inspection work	1 foreman	Half day	1000 HK$ per labor per day
Primer coating	2 workers	4 days	1000 HK$ per labor per day
Inspection work	1 foreman	Half day	1000 HK$ per labor per day
Texture coating	1 worker	1 day (per section of the wing)	1000 HK$ per labor per day
Inspection work	1 foreman	Half day	1000 HK$ per labor per day
Top coating	6 workers	3-4 month	1300 HK$ per labor per day
Inspection work	1 foreman	Half day	1000 HK$ per labor per day
Dismantling of the Gondola	3 workers	2 days	1000 HK$ per labor per day

Note: The data accumulated is based on the block-A building (16F) on the case study site.

The current task is labor-intensive and imposes many health and safety hazards. The worker is stationed inside the Gondola, which is suspended in great height. Due to wind, the Gondola will swing repeatedly, the gap between the gondola and the façade can be enlarged. Therefore, it is difficult to reach certain areas where the paint needs to be applied. Furthermore, the painter has to wear the protective facemask, and clothing to protect against the flying paint particles. Based on the data collected on-site, the research team considers the façade painting, namely the finishing task has having high potential to be improved by implementing automation and robotics technologies.

(2) The existing methods for interior painting are described below.

Existing methods for interior painting:

Table 3-4: Existing methods for interior painting

Description of the paint	MATEX AA EMULSION
Type	Acrylic PVA Copolymer emulsion coating
Color	Standard colors as per color card, subject to the design specification
Finish	Matt
Uses	Interior walls, Ceilings, Hard and soft boards
Features	Super valuable emulsion paint, Economical

	Washable (Wet scrub complies to ASTM D2486:96 Minimum 400 cycles) Fungus – Resistant Smooth appearance and easy application

Task application data of interior painting:

Table 3-5: Task application data of the current interior painting task

Method	Brush, roller and airless spray
Theoretical Coverage	Theoretical – 13.3m²/Liter Practical – Depends on substrate condition, application method etc.
Dilution	Use Clean water Brush – 15 – 30% Roller – 15 – 30% Spray – 15 – 30%
Surface Preparation	Ensure that the surface is clean and dry, free from oil, grease, algae, fungus and other foreign matter. Remove unstable paint film from previously painted surface. Do not apply when moisture content above 6% or 19% determine by Protimeter. For new surface, Vinilex 5101 Wall Sealer or Odour-less All-in-one Primer or Ultra Sealer III is recommended for optimum results. Do not apply in poor ventilated area, high humidity above 85% and cool weather <5°C
Drying Time	Touch Dry – 10 Mins Hard Dry 30 Mins Overcoat Time – 2 Hours
Cleaning	Wash all equipment immediately with clean water after use

Task analysis of interior painting:

Task	Labor	Time	Cost
Repair concrete wall surface	2 workers	2 weeks	800 HK$ per labor per day
Cleaning and preparation of the interior wall	3 workers	1 day	800 HK$ per labor per day
Painting X 3 coats	2 foremen	1 week	1200 HK$ per labor per day

Note: The data accumulated is based on one wing in the case study site.

(3) In the case study building, the locations require plastering are the area where tiles will be applied. The only areas that have tiles coverage are the communal areas outside the passengers lift.
The existing methods for interior plastering are described below:
Task analysis of interior plastering:

Table 3-6: Task analysis of the Interior plastering application

Task	Labor	Time	Cost
Repair concrete wall surface	2 workers	2 weeks	800 HK$ per labor per day
Cleaning and preparation of the interior wall	1 worker	1 day	800 HK$ per labor per day
Apply spatterdash	1 worker	2 days	1000 HK$ per labor per day
Rendering (plastering)	2 workers	1 week	1200 HK$ per labor per day

Note: The data accumulated is based on one wing in the case study site

In conclusion, based on the response from the on-site interviews and investigation, which indicate the PHC sector in Hong Kong has the potential and willingness to implement construction robotics and automation technology. Among the selected tasks, façade work, interior painting, and interior plastering have the higher potential to be automated. However, it is crucial to test and refine the proposed robotic application in a pilot project, in which the biggest challenge is to introduce construction robots into an on-going project without causing any delays.
Furthermore, based on the knowledge gained during the site visit, the project team proposed five automated systems as the long-term improvement goals to the status quo of the on-site tasks. They include: (1) automatic climbing formwork, (2) hoist and positioning System, (3) façade coating/ painting/ cleaning/ exterior finishing system, (4) interior painting system, and (5) interior plastering system. The proposed preliminary designs are demonstrated below.

(1) Automatic Climbing Formwork

Automatic climbing formwork refers to a special type formwork for vertical concrete structures that automatically rises along with the building process. While relatively complicated and costly, it can be an effective solution for buildings that are either very repetitive in form (such as towers or skyscrapers) or that require a seamless wall structure (using gliding formwork, a special type of climbing formwork). The proposed long-term schematic design of automatic climbing formwork aims to achieve 30% degree of automation (see *Figure 3-17*).

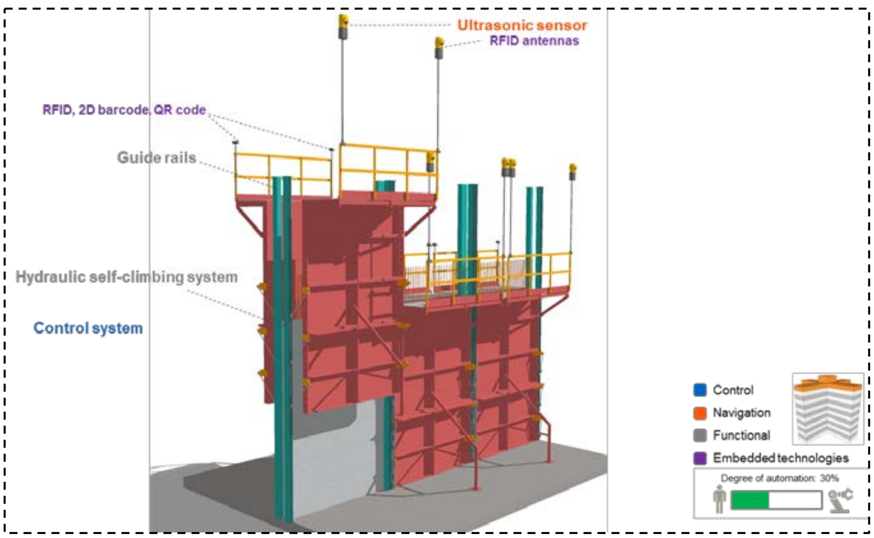


Figure 3-17: Proposed Automatic Climbing Formwork

(2) Hoist and positioning system

Robotic positioning aids and robotic crane end-effectors improve conventional systems and methods, and allow for precise pick-up and position/alignment operations. The proposed long-term schematic design of the hoist and positioning system aims to achieve 80% degree of automation (see *Figure 3-18*).

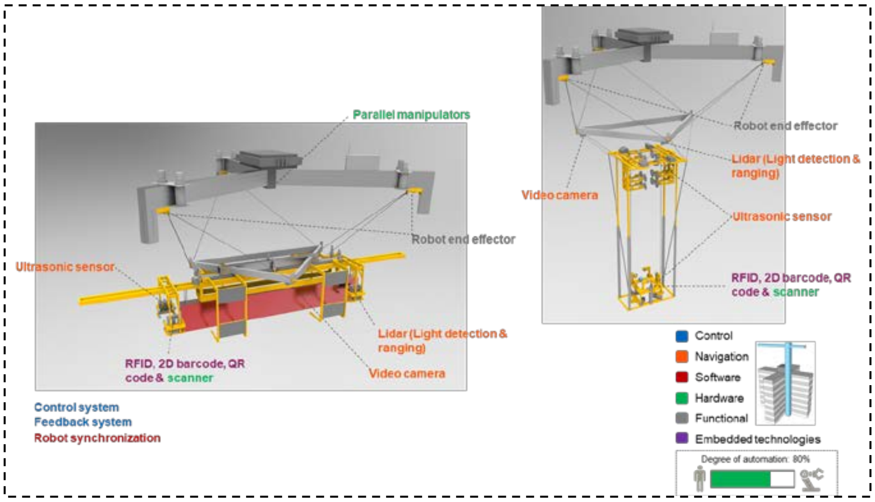


Figure 3-18: Proposed Hoist and Positioning System

(3) Façade coating/ painting/ cleaning/ exterior finishing system

Facade painting robots were developed to simplify the painting of building facades, especially for high-rise building. Facade painting robots have a particular advantage in keeping the quality constant. They usually have multiple spray nozzles operating in a synchronized mode. STCRs for painting use different strategies to move along the façade, such as suspended cage/gondola mechanisms, rail-guided mechanisms, and mechanisms allowing movement along the facade by vacuum or other adhesion technology. Other tasks on the façade, such as coating, cleaning, and exterior finishing, can be operated using the same mechanism as the façade painting robots. The proposed long-term schematic design of the façade robot system aims to achieve 80% degree of automation (see *Figure 3-19*).

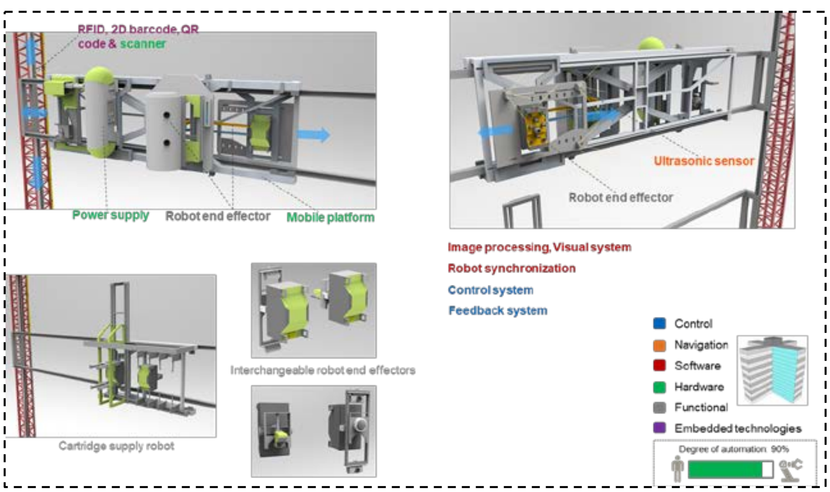


Figure 3-19: Proposed façade coating/ painting/ cleaning/ exterior finishing system

(4) Interior painting system

Interior painting robots are designed to substitute the interior painting workers. The proposed long-term schematic design of the interior painting system aims to achieve 70% degree of automation (see *Figure 3-20*).

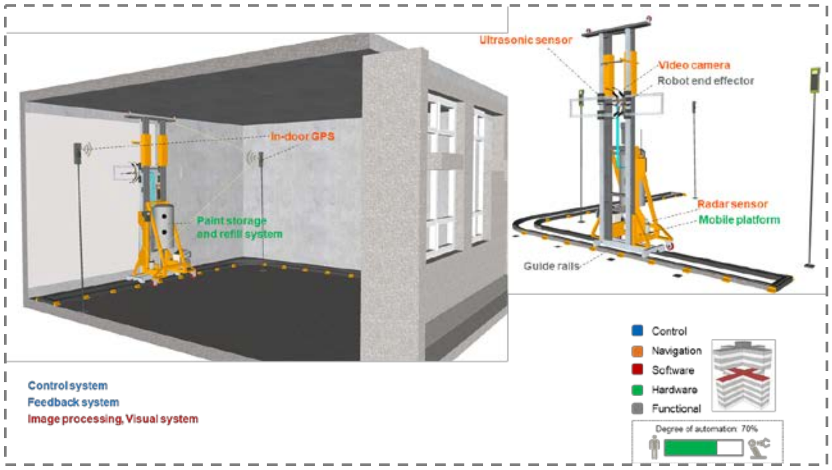


Figure 3-20: Proposed interior painting system

(5) Before the printing process starts, the concrete interior walls and ceiling need to be plastered. Interior plastering robots are designed to substitute the interior painting workers. The proposed long-term schematic design of the hoist and positioning system aims to achieve 90% degree of automation (see *Figure 3-21*).

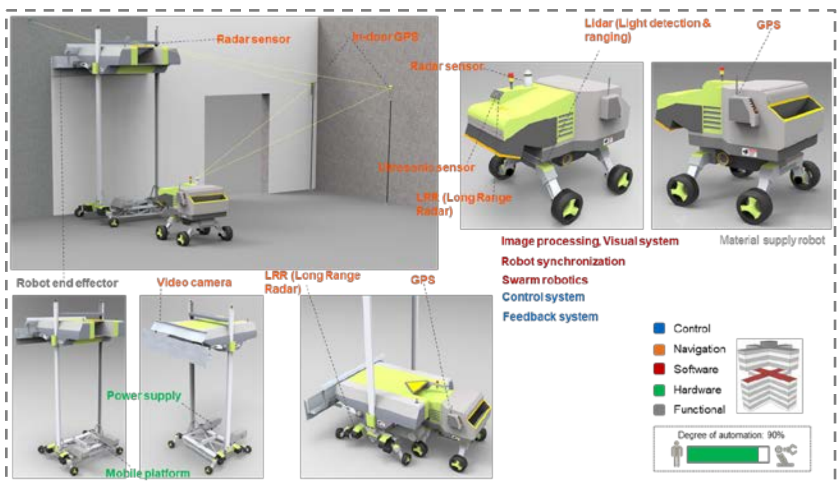
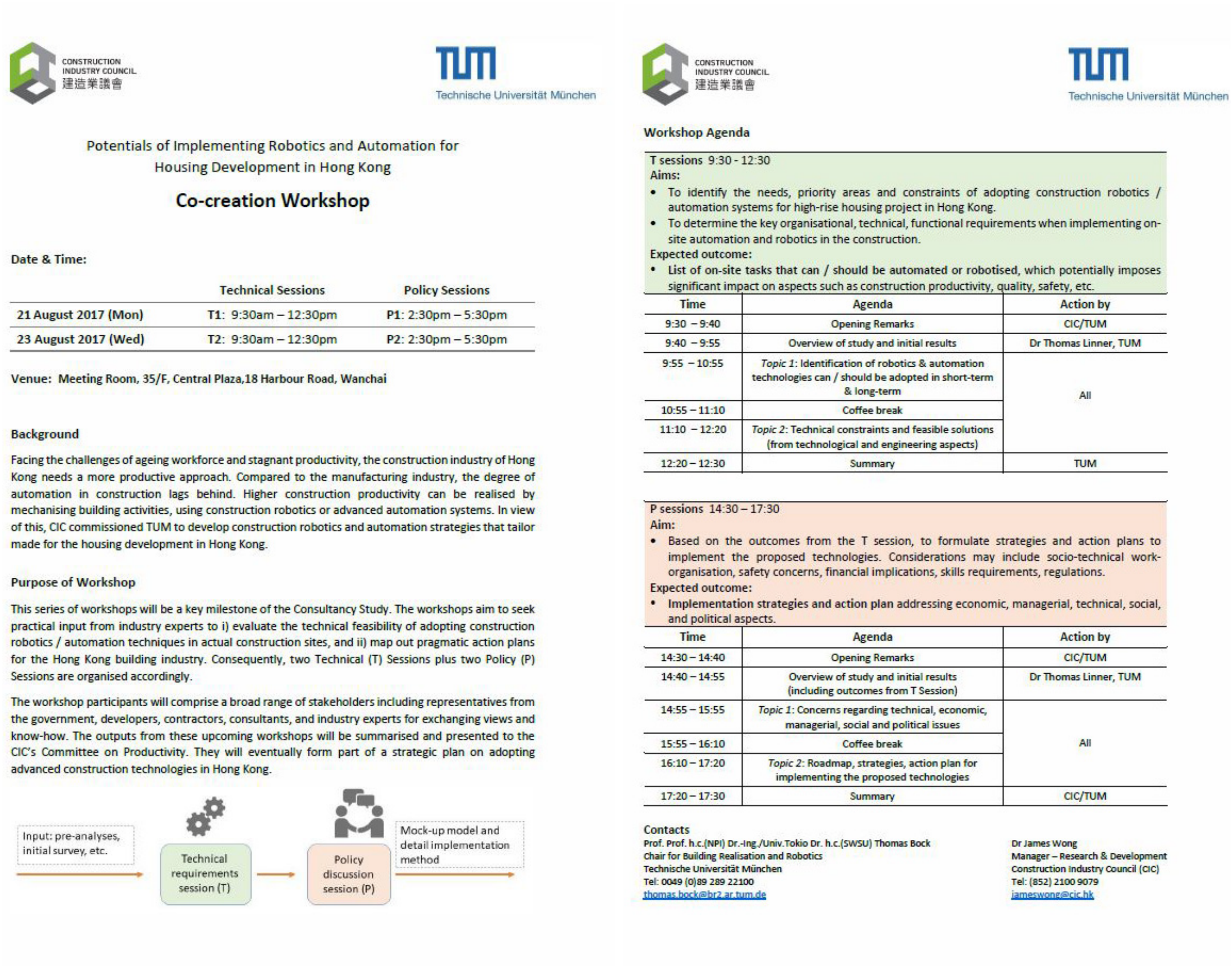


Figure 3-21: Proposed interior plastering system

3.4 Co-creation workshop (final selection, verification, and detailing of potential application areas)

Facing the challenges of ageing workforce, in addition to increasing construction demand and cost, the construction industry of Hong Kong needs a more productive approach. CIC commissioned TUM to develop construction robotics and automation strategies that are tailor-made for the housing development in Hong Kong. The proposed strategies may hold the key to a solution to the labor shortage issue, improving on-site safety and increase productivity while achieve a high level of quality. This series of workshops will be a key milestone of the Consultancy Study. The workshops aim to seek practical input from industry experts to i) evaluate the technical feasibility of adopting construction robotics / automation techniques in actual construction sites, and ii) map out pragmatic action plans for the Hong Kong building industry. Approximately 40 experts from industry, academia, government agencies, and non-governmental organizations are invited to participate in the workshop (see the agenda in *Figure 3-22*).



CONSTRUCTION INDUSTRY COUNCIL 建造業議會

Technische Universität München

Potentials of Implementing Robotics and Automation for Housing Development in Hong Kong

Co-creation Workshop

Date & Time:

	Technical Sessions	Policy Sessions
21 August 2017 (Mon)	T1: 9:30am – 12:30pm	P1: 2:30pm – 5:30pm
23 August 2017 (Wed)	T2: 9:30am – 12:30pm	P2: 2:30pm – 5:30pm

Venue: Meeting Room, 35/F, Central Plaza,18 Harbour Road, Wanchai

Background

Facing the challenges of ageing workforce and stagnant productivity, the construction industry of Hong Kong needs a more productive approach. Compared to the manufacturing industry, the degree of automation in construction lags behind. Higher construction productivity can be realised by mechanising building activities, using construction robotics or advanced automation systems. In view of this, CIC commissioned TUM to develop construction robotics and automation strategies that tailor made for the housing development in Hong Kong.

Purpose of Workshop

This series of workshops will be a key milestone of the Consultancy Study. The workshops aim to seek practical input from industry experts to i) evaluate the technical feasibility of adopting construction robotics / automation techniques in actual construction sites, and ii) map out pragmatic action plans for the Hong Kong building industry. Consequently, two Technical (T) Sessions plus two Policy (P) Sessions are organised accordingly.

The workshop participants will comprise a broad range of stakeholders including representatives from the government, developers, contractors, consultants, and industry experts for exchanging views and know-how. The outputs from these upcoming workshops will be summarised and presented to the CIC's Committee on Productivity. They will eventually form part of a strategic plan on adopting advanced construction technologies in Hong Kong.

Input: pre-analyses, initial survey, etc. → Technical requirements session (T) → Policy discussion session (P) → Mock-up model and detail implementation method

Workshop Agenda

T sessions 9:30 - 12:30
Aims:
- To identify the needs, priority areas and constraints of adopting construction robotics / automation systems for high-rise housing project in Hong Kong.
- To determine the key organisational, technical, functional requirements when implementing on-site automation and robotics in the construction.

Expected outcome:
- List of on-site tasks that can / should be automated or robotised, which potentially imposes significant impact on aspects such as construction productivity, quality, safety, etc.

Time	Agenda	Action by
9:30 – 9:40	Opening Remarks	CIC/TUM
9:40 – 9:55	Overview of study and initial results	Dr Thomas Linner, TUM
9:55 – 10:55	*Topic 1*: Identification of robotics & automation technologies can / should be adopted in short-term & long-term	All
10:55 – 11:10	Coffee break	
11:10 – 12:20	*Topic 2*: Technical constraints and feasible solutions (from technological and engineering aspects)	
12:20 – 12:30	Summary	TUM

P sessions 14:30 – 17:30
Aim:
- Based on the outcomes from the T session, to formulate strategies and action plans to implement the proposed technologies. Considerations may include socio-technical work-organisation, safety concerns, financial implications, skills requirements, regulations.

Expected outcome:
- Implementation strategies and action plan addressing economic, managerial, technical, social, and political aspects.

Time	Agenda	Action by
14:30 – 14:40	Opening Remarks	CIC/TUM
14:40 – 14:55	Overview of study and initial results (including outcomes from T Session)	Dr Thomas Linner, TUM
14:55 – 15:55	*Topic 1*: Concerns regarding technical, economic, managerial, social and political issues	All
15:55 – 16:10	Coffee break	
16:10 – 17:20	*Topic 2*: Roadmap, strategies, action plan for implementing the proposed technologies	
17:20 – 17:30	Summary	CIC/TUM

Contacts

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Figure 3-22: Co-creation workshop agenda

The workshop was divided into two sessions: a technical session (T-Session) and a political session (P-Session). The technical session focused on prioritizing on-site tasks necessary to be automated or robotized. Then, the workshop participants evaluate the identified task in detail, discuss technical constraints and propose feasible solutions. The political session focused on the policy context and summaries of soft requirements of the tasks, systems, which were selected in the technical session. Finally, participants discussed how to implement the selected systems, roles of the key stakeholders and the feasible business models (see *Figure 3-23*).

Figure 3-23: Photos taken from the co-creation workshop venue

The workshop offered a unique opportunity that brings a wide range of stakeholders from the construction industry together to discuss and exchange views and to share the outcomes from the initial study, online survey and on-site case study. The outputs from this upcoming workshop became the principle guidance that support the project aims and to map out strategies for implementing construction robotics or advanced automation systems in Hong Kong.

3.4.1 Workshop theme: T-session (21 August 2017)

The progress of the project was briefly introduced and the initial research including online survey results was shared with the workshop participants. The outcomes of the on-site case study and primary examples of proposed system designs were briefly introduced.

(1) Topic 1: identification of robotics & automation technologies that can/ should be adopted in short-term & long-term

This session focused on the identification of specific on-site tasks that experience the following challenges:

- Facing labor shortage
- Low productivity
- Poor construction quality
- High risks

To evaluate whether the identified on-site tasks can be improved by using automation or robotics, a vote was cast on the identified priority tasks:

- Automated formwork (votes received: 1)
- Component positioning (votes received: 0)
- Façade works, exterior works (votes received: 7)
- Interior plastering (votes received: 7)
- Interior painting (votes received: 10)
- Welding (votes received: 3)
- Rebar work, rebar fixing (votes received: 3)
- Systems for inspecting construction quality (votes received: 2)
- M&E works, including external building services (votes received: 3)

The general requirements for the top-ranked tasks (e.g., façade works & exterior works, exterior works & interior plastering, and interior painting) were identified as follow:

- To consider the relationship of application area/time vs. the setup time for the system on the site: the proposed system needs to be flexible and easy to install in the congested space on-site.
- To consider movement and logistics of the robots on the site:
- The proposed system needs to be compact, lightweight and easy to maneuver.
- To consider complex geometry of sites, buildings, floorplans, etc.:
- The proposed system needs to be easy to adapt to the different designs of the building.
- The use of sensors instead of temporary rails: the proposed system should avoid using temporary fixtures that will increase installation time.
- Semi-automatic approach: co-work of robots and humans on the site: the proposed system should consider human-robot interaction. The robotic system may not replace on-site labor, but should work together with labor to enhance

overall productivity. Ultimately, a group of robots might be supervised by only one worker

(2) <u>Topic 2: Technical constraints, feasible solutions and detailing selected task areas</u>
This session focused on detailing the top ranked tasks by formulating working sequences and summarizing the specific requirements for each task.

a. Façade works, exterior works
Sub-tasks:
- Installation of the Gondolas
- Cleaning and preparation of the external wall, skim coating
- Apply exterior paint (Primer, Texture and 2 coats of Top coating – usually all layers spray painting, sometimes apply 3rd layer or corners with rollers)
- Insertion/assembly of exterior piping
- Inspecting façade paint quality (paint inspection, window-water leakage test, etc.)
- Dismantling of the Gondolas

Specific requirements:
- Quality of the finish paint is highly important
- Minimize safety risks when operating the system
- Minimize distraction of other tasks (e.g. sometimes up to 80 gondolas work in parallel)
- Selective automation approach (e.g. robot paints large surfaces and human worker paint corners and areas, which are difficult to access for a robot).
- Various design approaches shall be analyzed both with and without installation rails that are theoretically possible, according to the architect, if housing authority demands and sets requirement, accordingly.

b. Interior painting, plastering:
Sub-tasks:
- Plastering, repairing of concrete wall (3-4 months before painting)
- Cleaning and surface preparation
- Material supply
- Painting: coating layer 1 and coating layer 2

Specific requirements:
- Minimize set-up time
- No additional works required would be ideal (fully autonomous system)
- Fully automated and not partially manipulated system is preferred
- Noise proof so it can be used during overnight shifts
- Improve safety on the site
- Increase speed may not be crucial
- Maintaining high quality is important

3.4.2 Workshop theme: P-session (21 August 2017)

The progress of the project was briefly introduced and the initial research including online survey results was shared with the workshop participants. The outcomes of the on-site case study and primary examples of the proposed system designs were briefly introduced as well as the preliminary results from T-sessions.

The various concerns and opportunities imposed through implementing the proposed systems were examined. Guidance and potential approaches were discussed in terms of how to address economic, managerial, social and political issues when introducing automation or robotics in the construction industry. Discussion around the business model topic was conducted, which aimed at supporting future implementation in the specific construction phase.

(1) <u>Topic 1: concerns regarding technical, economic, managerial, social and political issues</u>

Key soft requirements for the highest ranked tasks that were selected from the T-session are listed below:

- Regulations to accommodate and motivate implementation of automation and robotics
- Policy encouragement
- Work organization on-site
- Ergonomics, human-system interface
- Training for perspective workforce
- Create incentives for robot use (e.g., through the biding process, offered by CIC, BEAM, BIM, etc.)
- Certified the System
- Guarantee high quality of construction
- Guarantee improved safety on the site
- Build up robot supply infrastructure
- Workers-machine balance, upgrading the working environment
- Create attractive new jobs by implementing automation and robotics (i.e., select those tasks and priority areas or develop a selective automation approach that could achieve this goal)
- Consider feasible business models (e.g., 2-3 years payback time preferred)

(2) <u>Topic 2: Strategies, action plan and potential business model for the top ranked tasks that were selected from the T-session</u>

This session focused on issues related to establishing applicable business models for different end users. Business model components for the top ranked tasks that were selected from the T-session are listed below:

- A solution is needed for maintaining the robots. This can be achieved by internal training or outsourcing
- Beware of setting up the right degree of complexity for the robot (e.g. a more complex robot will be more autonomous, but will require a high investment and higher skills and maintenance cost, etc.)
- Initial cost & investment: 2-3 years payback time is favorable
- Consider frequency of use to avoid system redundancy
- Consider supply chain relationship between developer, contractor and sub-contractor, etc.
- Identify the orchestrator - The developer or the contractor. The experiences shared in the tunnel boring machine (TBM) distribution might offer valuable insight

3.4.3 Workshop theme: T-session (24 August 2017)

(1) <u>Topic 1: identification of robotics & automation technologies that can/ should be adopted in short-term & long-term</u>

The identified priority tasks are:

- Automatic formwork, including compaction of concrete, man access, 3d printing of formwork (votes received: 5)

- Hoist and positioning in combination with prefabricated elements (votes received: 7)
- Exterior façade works, including painting, piping, cleaning (votes received: 4)
- Interior painting (votes received: 0)
- Interior plastering (votes received: 1)
- Work related to reinforcement works on the site (votes received: 0)
- Foundation works (votes received: 0)
- Water leakage testing (for each window after completion of building exterior)
- Compaction of concrete (votes received: 0)
- Automated horizontal/vertical welding of prefabricated components connections on the site (votes received: 5)
- Drilling works (votes received: 0)
- Stone finishes (votes received: 0)
- Quality control (votes received: 0)
- Line marking (votes received: 0)
- Construction progress monitoring (votes received: 0)
- Logistics on the site (votes received: 1)
- M & E works in the lift shafts (votes received: 0)
- Tower crane operations (votes received: 6)

The general requirements for the top ranked tasks (e.g., Hoist and positioning in combination with prefabricated elements, tower crane operations, automatic formwork, and automated welding were identified as follow:

- To consider the compatibility of platform technologies between various robot applications: e.g. BIM, VR, sensors on board, global sensors such as drones for sensing and inspection, etc. etc.
- To consider some repetitive tasks can be solved by a machine learning approach (i.e., the robot learns from application to application)

(2) Topic 2: Technical constraints, feasible solutions and detailing selected task areas

This session focused on detailing the top ranked tasks by formulating working sequences and summarizing the specific requirements for each task.

a. Hoist and positioning & tower crane:

Sub-tasks:

- Hooking (end-effector, automated, etc.)
- Installation, climbing task
- Ground logistics and crane feeding, automate temporary loading bucket on ground
- Logistics to the site/ JIT
- On site task decision support module
- Banks man’s collaborative work
- Containing and reducing over-sailing

Specific requirements:

- Control mode/ Human-computer interaction (HCI)
- To consider platform technologies. Different ranges, specifications of systems based on a common platform design. This will ease system upgrading and manufacturing
- Minimize the impact of the on-site construction cycle
- Provide ICT support with decision making and scheduling

- To ensure usability aspect of the proposed system. The system is easy to operate by existing workforce
- Increase safety on the site
- Increase productivity on the site (reduction of labor, increase speed, e.g., through faster hoisting procedure, etc.)

b. Automatic formwork:
   Sub-tasks:
   - Worker access & to facilitates cooperation between various trades
   - Concrete compaction
   - Rising/climbing
   - Dismantling
   - Smart form (e.g., integrated quality inspection, concrete temperature measurement and control, etc.)
   - Support with organization and scheduling.

   Specific requirements:
   - Control mode/Human-computer interaction (HCI)
   - Consider platform technologies
   - Main obstacle: cost
   - Government needs to guarantee robot quality, safety, etc. through certification, regulation and training.
   - Consider minimal margins of 3% in public housing
   - Systematization and modularization of smart formwork needed

c. Automated welding on the site:
   Sub-tasks:
   - To weld temporary elements
   - To weld permanent elements
   - To gain access on higher floor levels with covered walkways
   - Perhaps move all welding tasks off-site

   Specific requirements:
   - High mobility/flexibility is needed, may be to propose a “spider like robot”
   - To consider carefully which work can be shifted to an off-site facility
   - Overnight or 24/7 operation
   - Robot needs to deliver/ensure structural quality of the welding part and to avoid defects (in particular related to statics)
   - Enhance safety on the site
   - Changeable end-effectors for different tasks (e.g. the same robot may be used for 3D-printing of formwork)

3.4.4 Workshop theme: P-session (24 August 2017)

(1) <u>Topic 1: Concerns regarding technical, economic, managerial, social and political issues</u>

Key business model for the top ranked tasks that were selected from the P-session are listed as below:

- To define the degree of prefabrication and to determine the remaining tasks that robots should focus on
- How to combine the use of robotic and BIM and to favor smaller companies
- To consider fierce completion among contractors and small margins in the public housing

- Robotics may require change in the whole ecosystem; to establish a new industrial network
- Due to confined site space, robots need to be very flexible and mobile
- To create incentives and minimize the risks for companies that might be willing to adopt the approach (e.g. through cheap loans)
- To consider robot application as early as possible in the design process. It is necessary to adopt Robot-Oriented Design (ROD) **(Bock & Linner, Robot-Oriented Design, 2015)**
- Starting with low-risk, simple tasks, then move onto more complex tasks
- It is highly recommended to evaluate performance through pilot projects
- To certify the performance of robots or automated systems
- To analyze TBM adoption and to extract experiences from it

(2) Topic 2: Strategies, action plan and road map draft

- Phase 1: Task identification
- Phase 2: Detailed design and final selection of the mock-up based on a selected system
- Phase 3: To adopt modular design approach for various systems. To identify robot supply infrastructure
- Phase 4: 1:1 scale prototype(s)
- Phase 5: To conduct pilot projects
- Phase 6: Robot performance certification and system setup
- Phase 7: Training and government policy measures (develop strategy for industry incentives, to minimize risks, dissemination, etc.)
- Phase 8: Implement robot supply infrastructure and to implement strategies for introducing incentives, risk minimization
- Phase 9: To introduce plug-and-play design approach and to implement robots on-site

3.5 Final selection and description of priority areas

The workshop along with the survey and on-site case study provide an extensive insight, which indicate how the construction industry in Hong Kong rationalizes the implementation of automation and robotics on-site. Based on these results, a system key performance analysis is conducted to identify the priority areas for the project.

3.5.1 System key performance analysis

The key performance of the selected system include safety, labor shortage, improvement of quality, adoptable, compact and flexible design, acceptance, and improvement of productivity. The spider chart is used as a metric to demonstrate a dynamic trend of the influential key performance, and each one is rated from low to high variables. For example, in this case, 5 point indicates a better performance score than 4 point. There were 5 finalists chosen for the evaluation, which include façade work and exterior work system, interior painting, plastering system, hoist and positioning system, automatic formwork, and automated welding system. Each system will receive a score based on the assigned performance criteria. The performance criteria can be described below:

- Safety: the system will improve operational safety and reduce health and safety hazards
- Labor shortage: the system will fill the labor shortage gaps

- Improvement of quality: the system will improve the working process and the final quality of the specific task
- Adoptable, compact and flexible design: the system is flexible and can be easily adopted to existing construction industry
- Acceptance: The system is in the favor of the construction industry. The finalized system can be implemented relatively straightforward without causing additional complications
- Improvement of productivity: the system will evidently improve productivity of the specific task

(1) The spider chart below (see *Figure 3-24*) demonstrates the key performance scores of the façade work & exterior work system.

- Safety (scored 5): The majority of the façade or exterior tasks can impose high-risk for the worker. The proposed system can improve operational safety significantly
- Labor shortage (scored 4): Façade or exterior task experiences labor shortage, and a worker has to receive special training to operate the suspended working platform
- Improvement of quality (scored 4): To remain high standard of quality is very important and the system can improve the working process and the final quality
- Adoptable, compact and flexible design (scored 4): The system can be designed by using platform strategy to achieve high flexibility
- Acceptance (scored 5): The system was popular among the participants during the workshop. There was no obvious objections to the concept
- Improvement of productivity (3): The system need to be tested through a pilot project to prove this hypothesis

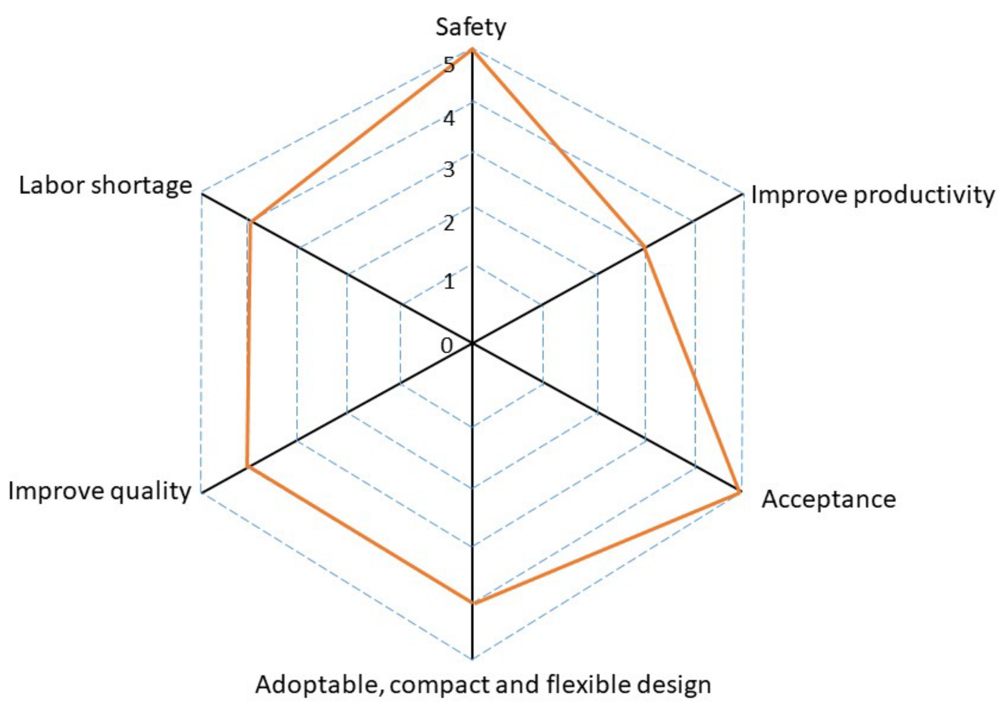


Figure 3-24: Spider chart showing the key performance scores of the façade work & exterior work system

(2) The spider chart below (see *Figure 3-25*) demonstrates the key performance scores of the interior painting, plastering system.

- Safety (scored 3): The current work is carried out under a relatively safe environment
- Labor shortage (scored 3): The current labor market can cope with the market demand
- Improvement of quality (scored 3): The current quality is reasonably high which was achieved by skilled labor. The system needs to be tested through a pilot project to prove this hypothesis.
- Adoptable, compact and flexible design (scored 3): The system needs to be highly adoptable to allow the system to be implemented in different floor layouts. It is challenging to achieve this under current site conditions
- Acceptance (scored 4): The system was recommended during the workshop.
- Improvement of productivity (3): The systems need to be tested through a pilot project to prove this hypothesis

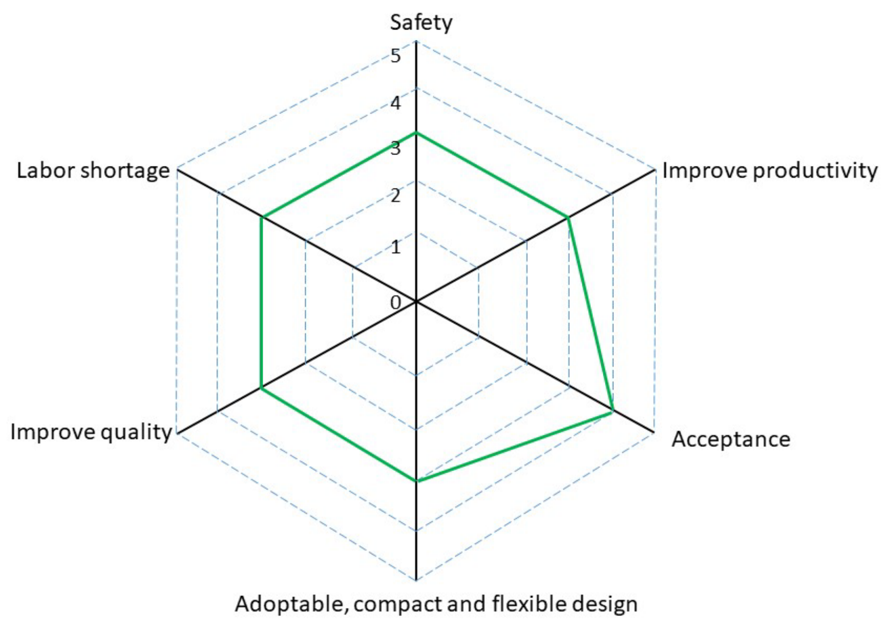


Figure 3-25: Spider chart showing the key performance scores of the interior painting, plastering system

(3) The spider chart below (see *Figure 3-26*) demonstrates the key performance scores of the hoist and positioning & tower crane system.

- Safety (scored 5): The current work is very risky, there are many concerns under the hoisting and crane safety, e.g. material falling, overloading, human error. So the proposed system can improve hoisting and crane safety
- Labor shortage (scored 3): The current labor market can cope with the market demand, although the labor cost is very high for the crane operator
- Improvement of quality (scored 2): The system needs to be tested through a pilot project to prove this hypothesis
- Adoptable, compact and flexible design (scored 3): It is challenging to modify or upgrade hoisting and crane systems. The existing systems need to be certified by the industry authority
- Acceptance (scored 2): The system was recommended during the workshop. However, it is extremely time-consuming and risky to use it for a pilot project. Additionally, if the system testing is only done under a lab environment, the results might be less comprehensive

- Improvement of productivity (3): The system needs to be tested through a pilot project to prove this hypothesis

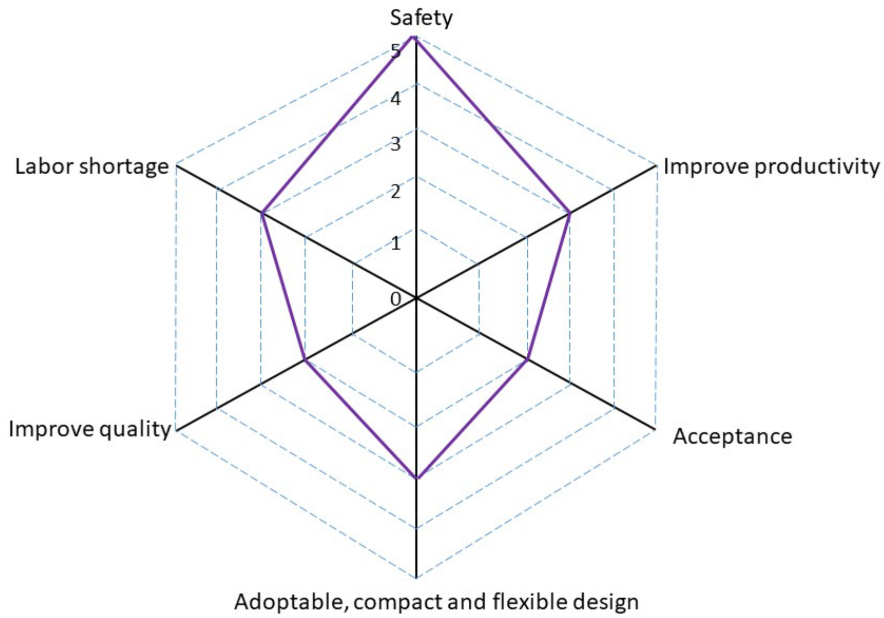


Figure 3-26: Spider chart showing the key performance scores of the hoist and positioning & tower crane system

(4) The spider chart below (see *Figure 3-27*) demonstrates the key performance scores of the automatic formwork system.

- Safety (scored 5): The current operation is very risky, and there are many concerns regarding to formwork erection and dismounting. So, the proposed system can improve operation safety
- Labor shortage (scored 3): The current labor market can cope with the market demand, although the labor cost is very high for the crane operator
- Improvement of quality (scored 4): Self-climbing formwork provides an example that the proposed system can further improve the working process as a whole
- Adoptable, compact and flexible design (scored 5): The existing self-climbing formwork systems are designed to be very flexible. The proposed system will take this feature as a reference
- Acceptance (scored 2): The system was recommended during the workshop. However, it is extremely time-consuming and risky to use it for a pilot project. Additionally, if the system testing is only done under a lab environment, the results might be less comprehensive
- Improvement of productivity (4): Self-climbing formwork provides an example to illustrate the proposed system can potentially improve productivity

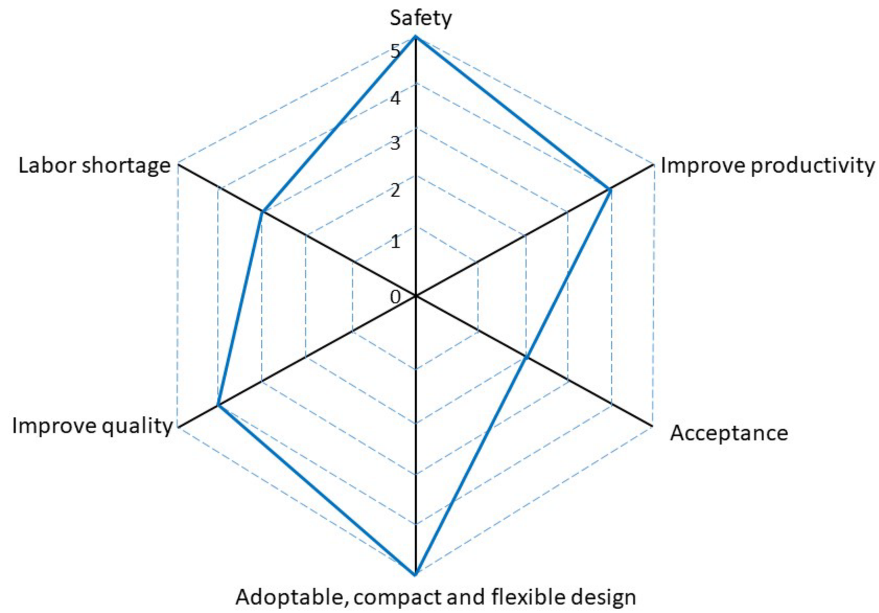


Figure 3-27: Spider chart showing the key performance scores of the automatic formwork system

(5) The spider chart below (see *Figure 3-28*) demonstrates the key performance scores of the automated welding on-site.

- Safety (scored 4): The current work is very risky, especially health hazards and personal injury proposed system can improve operation safety drastically
- Labor shortage (scored 5): This task experiences high labor shortage, and the worker has to receive special training to be able to work on-site. The labor cost for the welder is high
- Improvement of quality (scored 5): Many other industries rely on welding robots to improve welding quality. This may show a similar trend in the construction industry
- Adoptable, compact and flexible design (scored 4): Welding systems can be designed to be highly flexible and versatile, thus capable of different welding applications
- Acceptance (scored 3): The system was recommended during the workshop. However, it is extremely time-consuming and risky to use it for a pilot project. Additionally, if the system testing is only done under a lab environment, the results might be less comprehensive

  Improvement of productivity (scored 3): The system needs to be tested through a pilot project to prove this hypothesis

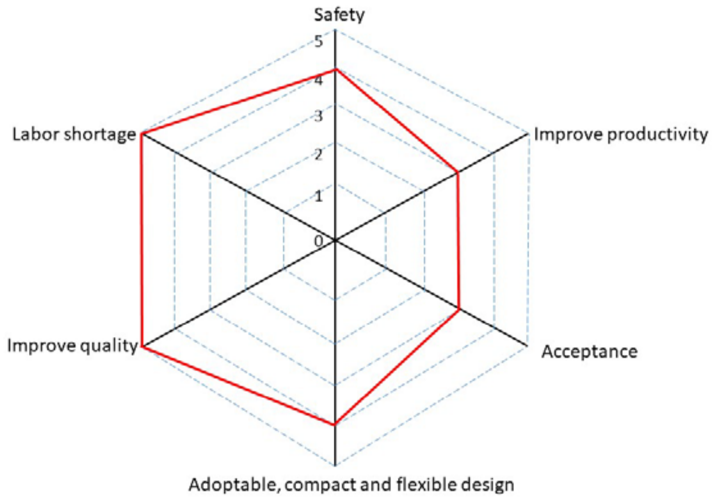


Figure 3-28: Spider chart showing the key performance scores of automated on-site welding

(6) Key insight: the superimposed spider chart below (see *Figure 3-29*) demonstrates a dynamic trend of the influential key performance that scored by each individual system.

- Safety has been identified as one of the most critical criteria for façade and exterior work system, automatic formwork and hoist system, positioning & tower crane
- Adoptable, compact and flexible design has been identified as the second most dominant measure. This was also pointed out by participants a few times over the workshop; the proposed system has to be adoptable to the changes of the on-site environment, building layouts and design features
- The proposed system needs to address increasing trend of labor shortage, and to improve finishing quality as well as productivity
- In general, based on the acceptance scores, the construction industry is open to implement automation and robotics
- To convince the stakeholders to willingly adopt automation and robotics on-site, we have to carry out a compelling pilot project with attractive incentives, which requires help from the government
- In summary, the façade work and exterior work system received a total score of 25; the interior painting and plastering system received a total score of 19; the hoist and positioning system received a total score of 18; the automatic formwork received a total score of 23; and automated welding system received a total score of 24.
- Therefore, taking the budget and time into consideration, the project team together with the workshop participants decided to choose the façade work and exterior work system as the top priority of further research and development in this project.

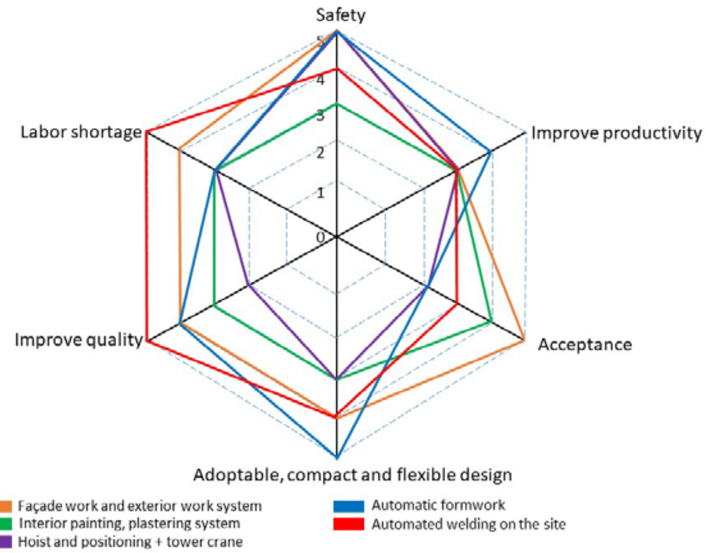


Figure 3-29: Summative spider chart showing a dynamic trend of the influential key performance that scored by each individual system

3.5.2 Conclusion and plan for the next phase

The workshop along with the survey and on-site case study provide an extensive insight, which indicate how the construction industry in Hong Kong rationalizes the implementation of automation and robotics on-site. In general, the responses from the industry, academia, and government agencies are positive. Four key challenges faced by the construction industry were identified, which include labor shortage, low productivity, poor construction quality, and high risks on-site. The T-session of the workshop identified on-site tasks that can be potentially improved by implementing automation and robotics. The T-session also detailed the top ranked tasks by formulating their working sequences, sub-tasks and summarizing the subsequent requirements. The P-session was dedicated to discuss economic, managerial, social and political issues when introducing automation or robotics on-site. The discussion was conducted in accordance with the experience and expertise of the participants. A systemic approach that reviewed the strategies may be applicable when engaging key stakeholders in addition to how to conduct final implementation in a later stage. Last, but not least, several different types of business model propositions were examined and the system for next phase was proposed.

<u>Plan for the next phase:</u>

- To investigate the kinematics, function, and design of the proposed system (namely the façade and exterior work)
- To analyze off-the-shelf products, then to identify if they can be integrated with the design
- To identify the basic specification of the proposed system
- To explore the detailed design systematically
- To construct a scale mock-up that demonstrates the basic operational features
- To engage contractors in Hong Kong and to measure stakeholder’s responses and feedback
- To upgrade and finalize the proposed design
- To prepare the system for the pilot project

3.6 Conclusions

Key insights and outcomes with regard to the identification of priority areas for on-site robotics applications in Hong Kong's public housing construction sector in this chapter:

1. The methodology for identifying the priority areas in Hong Kong's public housing construction sector is explained (e.g., pre-identification of technologies, online survey, on-site case study, co-creation workshop).
2. The 17 construction robotics and automation systems in three scenarios are initially identified.
3. The methodology and results of the online survey are revealed.
4. The key findings of the on-site case study of a Hong Kong housing construction project are described.
5. The process and results of the co-creation workshop are reported.
6. The method and decision of the final selection of 5 priority areas (i.e., façade processing robot system) are introduced.

4 Exemplary detailing of priority area "façade-processing"

Based on the key results of the *Chapter 3*, the aim of this chapter is to investigate the kinematics, function, and design of the proposed façade and exterior work robot system. In particular, the detailed design of the system, the exchangeable plug-and-play end-effector system, and the positioning system will be explained in detail. This stage of the research helps the project team to develop the prototype/mock-up system which is explained in detail in the *Chapter 5*.

4.1 The proposed design of the robot system

The proposed façade and exterior work robot is based on a suspended platform system which is commonly known as the gondola and widely used in Hong Kong construction industry for various façade tasks. Supported by the common roof supporting system, the robot can descend from the top to the bottom of a high-rise building while executing a task. Two electric motors near the hoisting devices on top of the robot are used to actuate the up and down movement. Through the addition of various sensors, the ultimate goal is to achieve a fully automated façade processing robot system, so the robot can be easily started and operated by no more than one worker. In addition, several workers can also stand on the gondola platform in case of inspection, repair, and supply, if needed. The robot system is highly modularized, meaning that the shape and size of the robot can be easily changed in accordance with the design of the target buildings. The detailed design is shown in *Figure 4-1*, and the sequence visualization of the façade robot when executing the painting function is demonstrated in Figure 4-2.

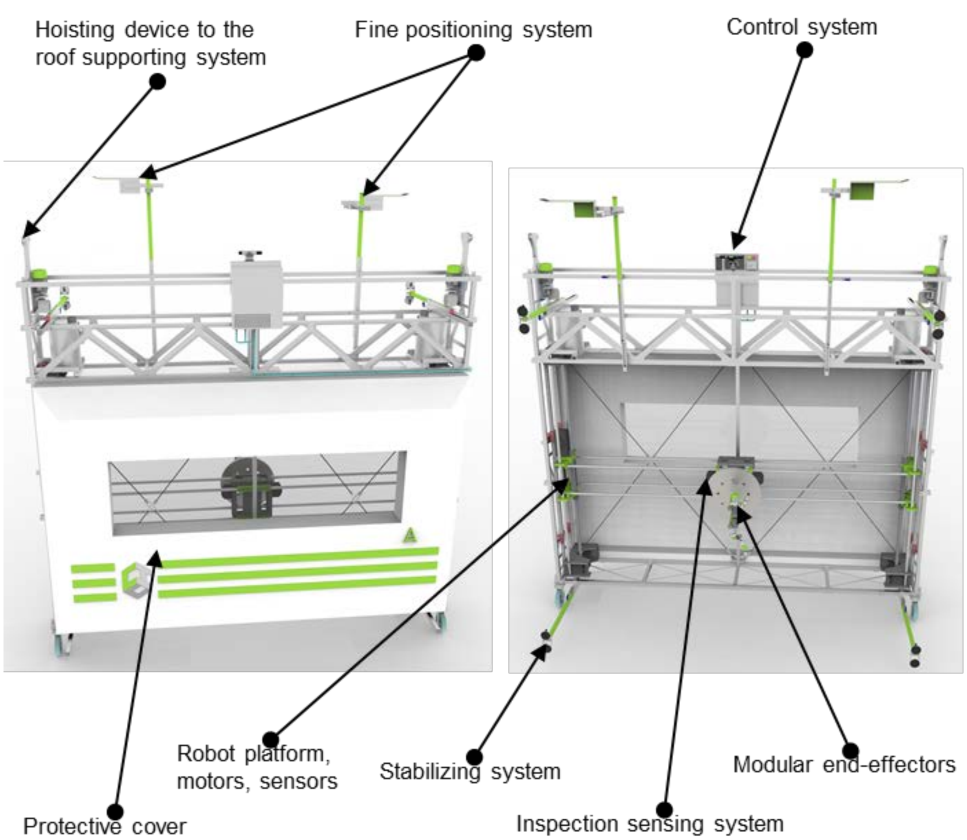


Figure 4-1: Proposed façade robot explained

The painting end-effector of the proposed system has 6 degree of freedom (DOF). Therefore, the fully functional system will be able to print each corner of the building façade.

Figure 4-2: Working process of the façade robot with painting function

The conventional roof supporting system, which is widely used in Hong Kong's construction sites, can support the robot. Suspension mechanism consists of a front beam, middle beam, rear beam, front base, an upper column, a counter weight, reinforcing steel rope, and an adjusting bar. The middle beam is inserted into the front beam and the rear beam, and the length can be adjusted to suit the working site. Height from the suspension beam to the ground can also be flexibly adjusted from 1.1m to 1.8m. Casters are installed on the front base and the rear base to be able to easily move the suspension mechanism. The quantity of the counterweight will be decided according to the robot system. The design of the roof supporting system is visualized in *Figure 4-3*.

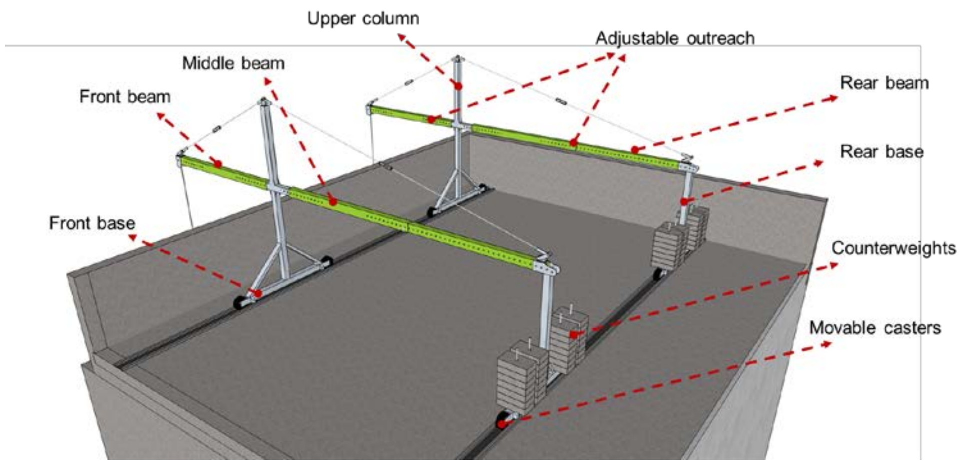


Figure 4-3: Roof supporting system for the suspended platform

4.2 Changeable versatile plug-and-play end-effector system

In order to broaden the capability of the robot, a changeable plug-and-play end-effector system is proposed. Therefore, the robot not only can perform the façade painting task, but also has the capability to perform other façade and exterior tasks without a purchase of a new robot. The proposed different methods to change the end-effector, the various plug-and-play end-effectors, and the potential building application scenarios will be introduced in this section as follows.

4.2.1 Different modes to change the end-effector

In order to realize the changeable plug-and-play end-effector function, three options can be proposed, including the manual mode, the "Swiss Army Knife" mode, and the supply robot mode. These options are explained as follows.

(1) Manual mode

In the manual mode, the trained construction worker can supply paint or water to the robot when it runs out of the respective resource. When the task needs to be changed (e.g., from painting to inspection), the worker can also simply replace the end-effector by hand on the job-site whenever necessary (see *Figure 4-4*).

Figure 4-4: Manual mode

(2) "Swiss Army Knife" mode

In this mode, the robot has a multi-functional rotatable end-effector toolset with multiple end-effectors integrated in the same robot. The lowest position of this toolset is the active position. When a specific task needs to be executed, the rotatable toolset will rotate the relevant end-effector to the active position, so that the needed task can be performed. In this mode, the water / paint still needs to be manually supplied by the worker (see *Figure 4-5*).

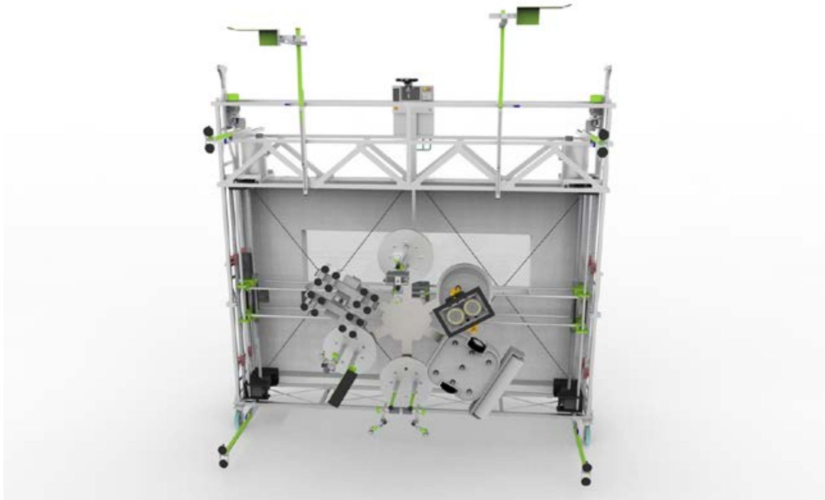


Figure 4-5: "Swiss Army Knife" mode

(3) Supply robot mode

In this mode, in addition to the main robot (Robot A), a smaller supply robot (Robot B) is designed to provide paint / water supply or to change the main robot's function by switching its end-effector (see *Figure 4-6*).

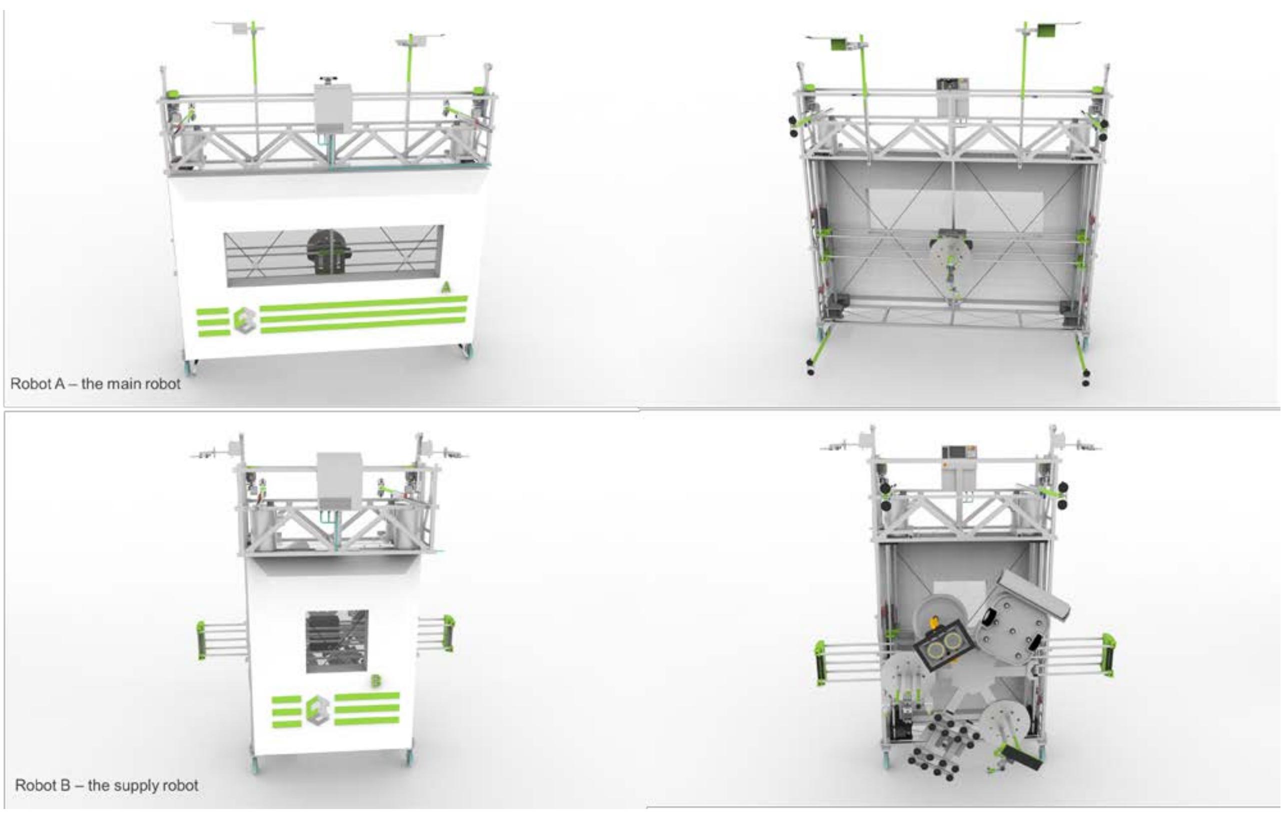


Figure 4-6: Supply robot mode

Figure 4-7 demonstrates the on-site working concept of the main robot (Robot A) and the supply robot (Robot B), and *Figure 4-8* is the flowchart showing the algorithm how Robot A & B will collaborate on-site.

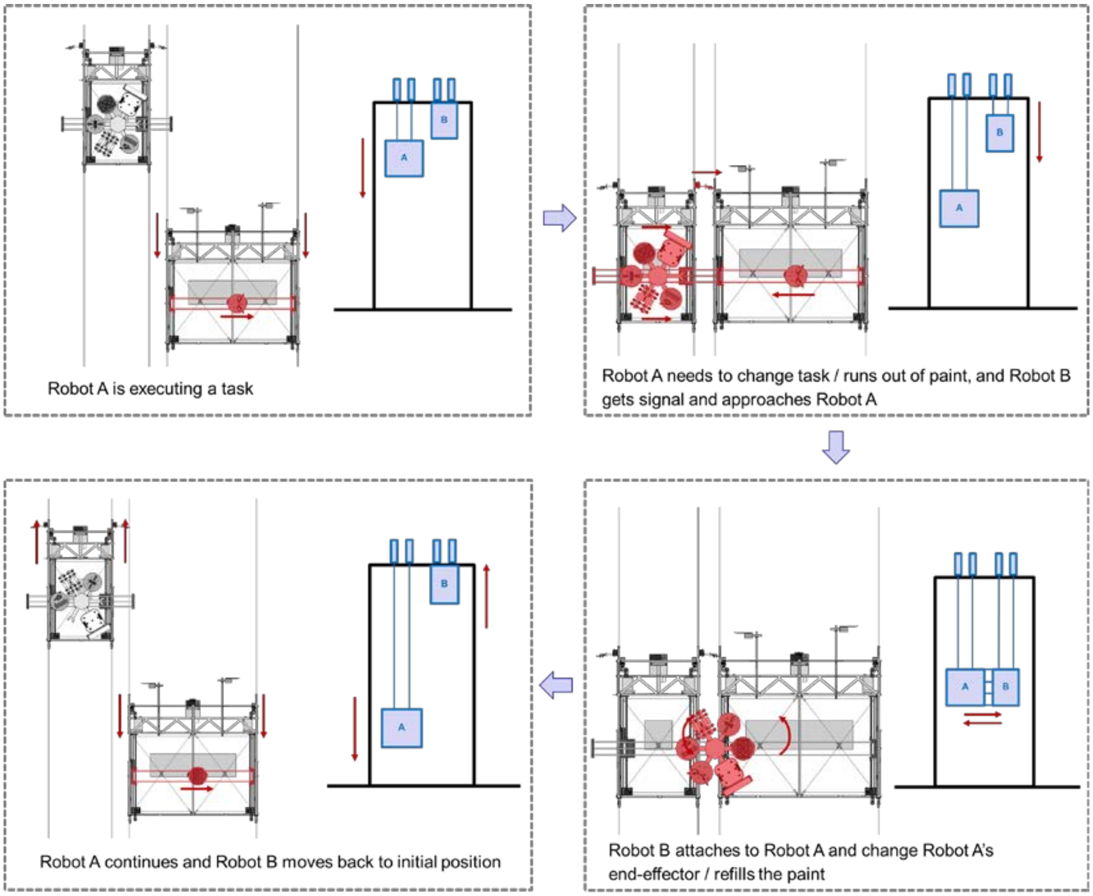


Figure 4-7: Robot A & B working concept

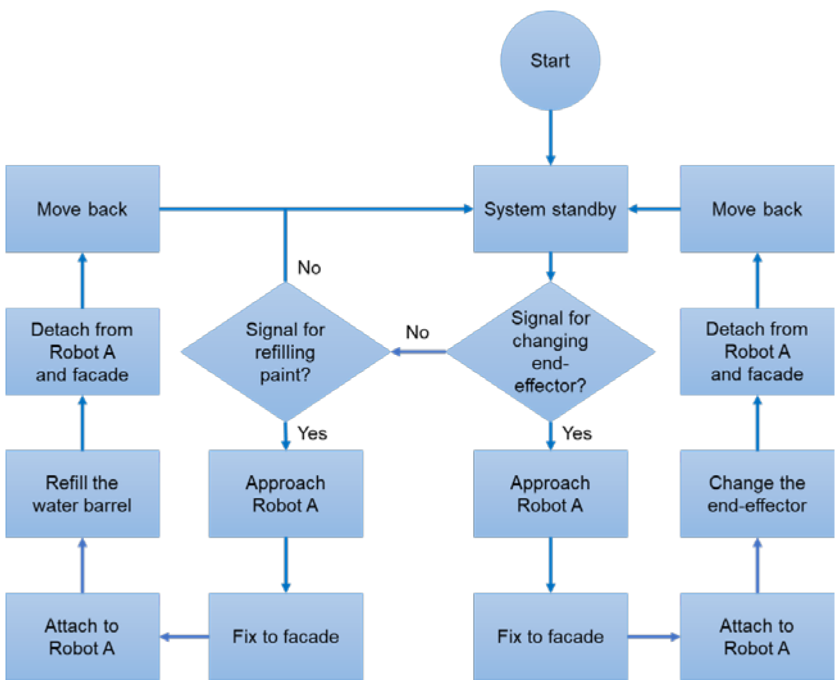


Figure 4-8: Algorithm flowchart of Robot A & B collaboration

4.2.2 *Various plug-and-play end-effectors*

The project team has identified nine different façade / exterior tasks, which can be automated in the foreseeable future, including fine plastering, grinding, painting, inspection

& marking, cleaning, leakage detection, fire extinguishing, façade installation & replacement, and piping installation. The detailed design of the various proposed end-effectors, as well as their algorithm flowcharts are listed as follows (see *Figure 4-9* to *Figure 4-19*). Please note that these flowcharts only show the abstract concept of how each end-effector works. For simplicity, the inspection loops are not added here because the inspection method for each task is different. The details of various end-effectors will be deliberated in the follow-up projects.

(1) Fine plastering

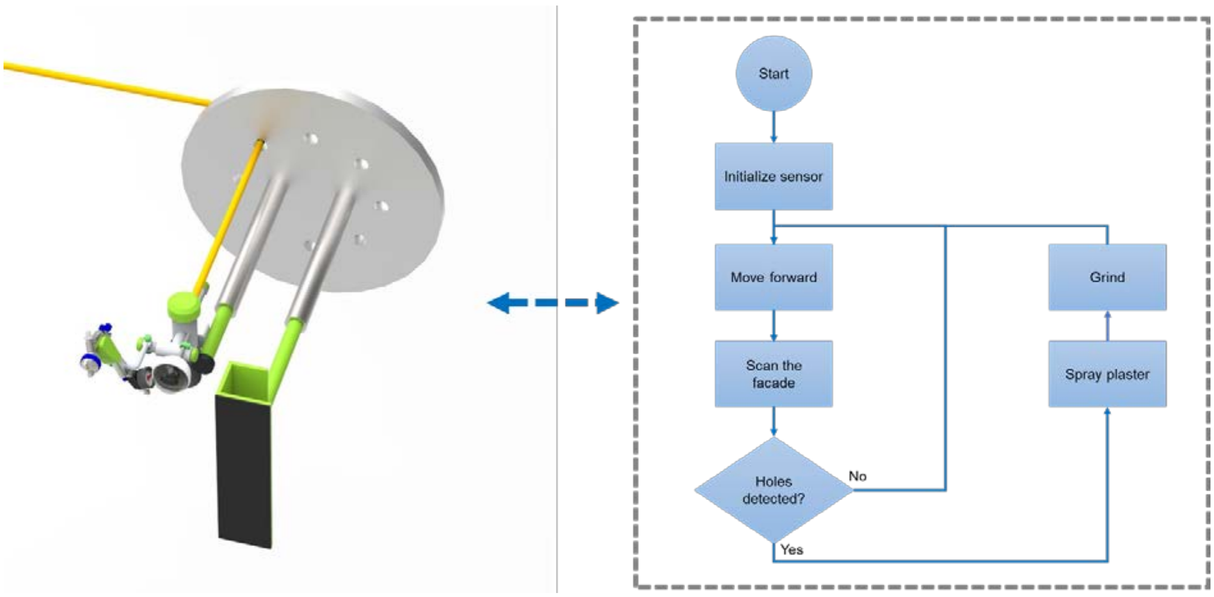


Figure 4-9: Fine plastering end-effector and its algorithm flowchart

(2) Grinding

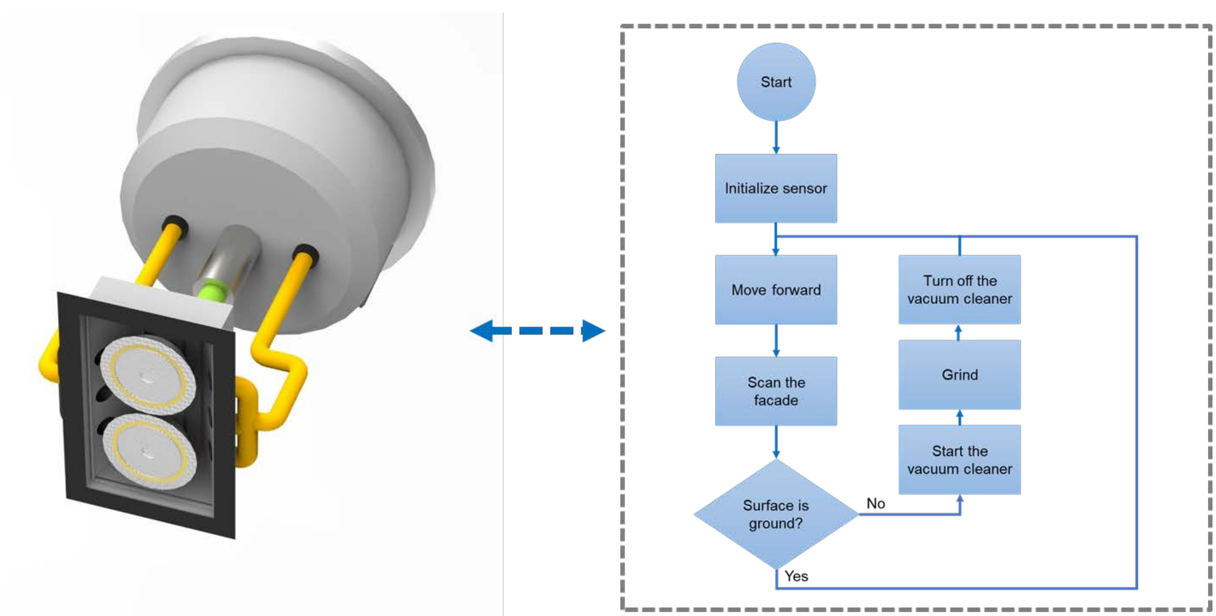


Figure 4-10: Grinding end-effector and its algorithm flowchart

(3) Painting

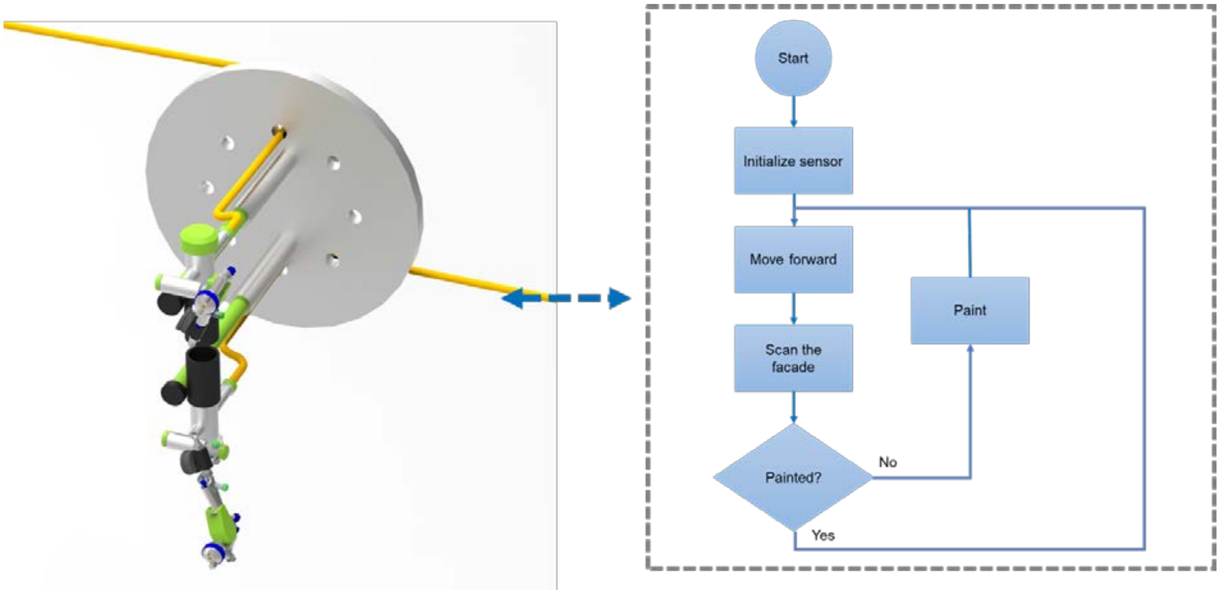


Figure 4-11: Painting end-effector and its algorithm flowchart

(4) Inspection and marking

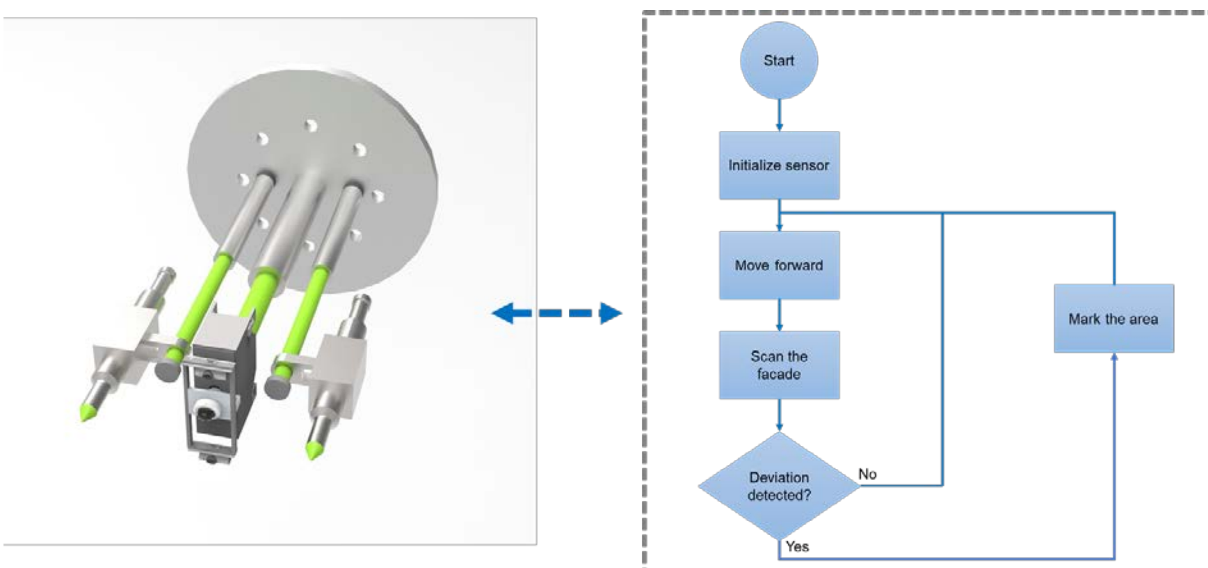


Figure 4-12: Inspection & marking end-effector and its algorithm flowchart

(5) Cleaning

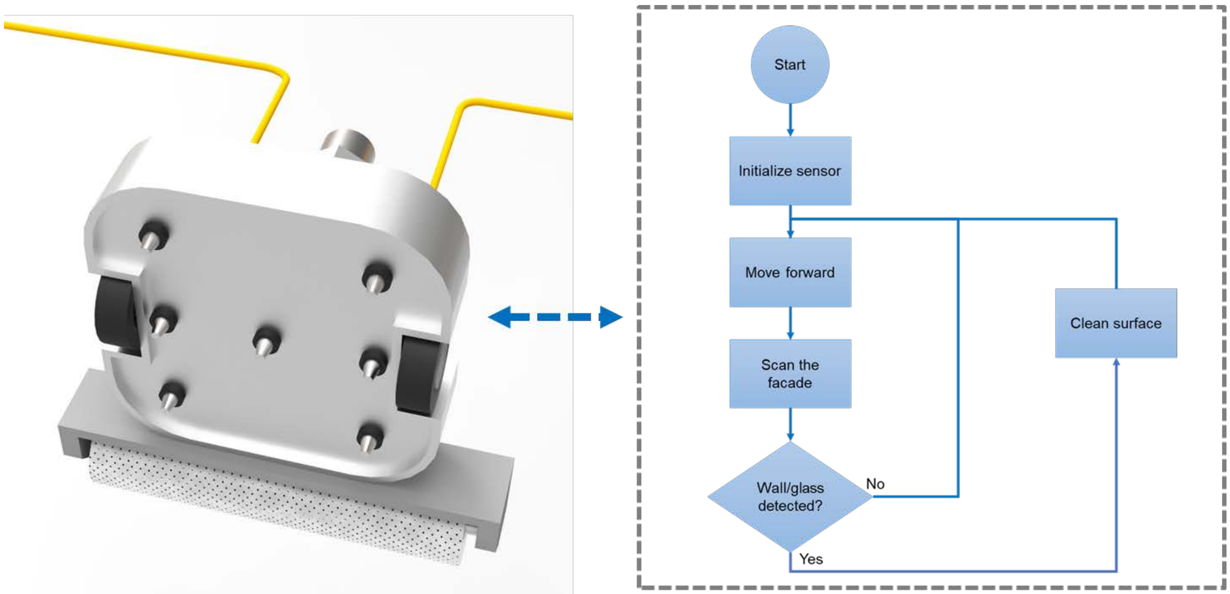


Figure 4-13: Cleaning end-effector and its algorithm flowchart

(6) Leakage detection

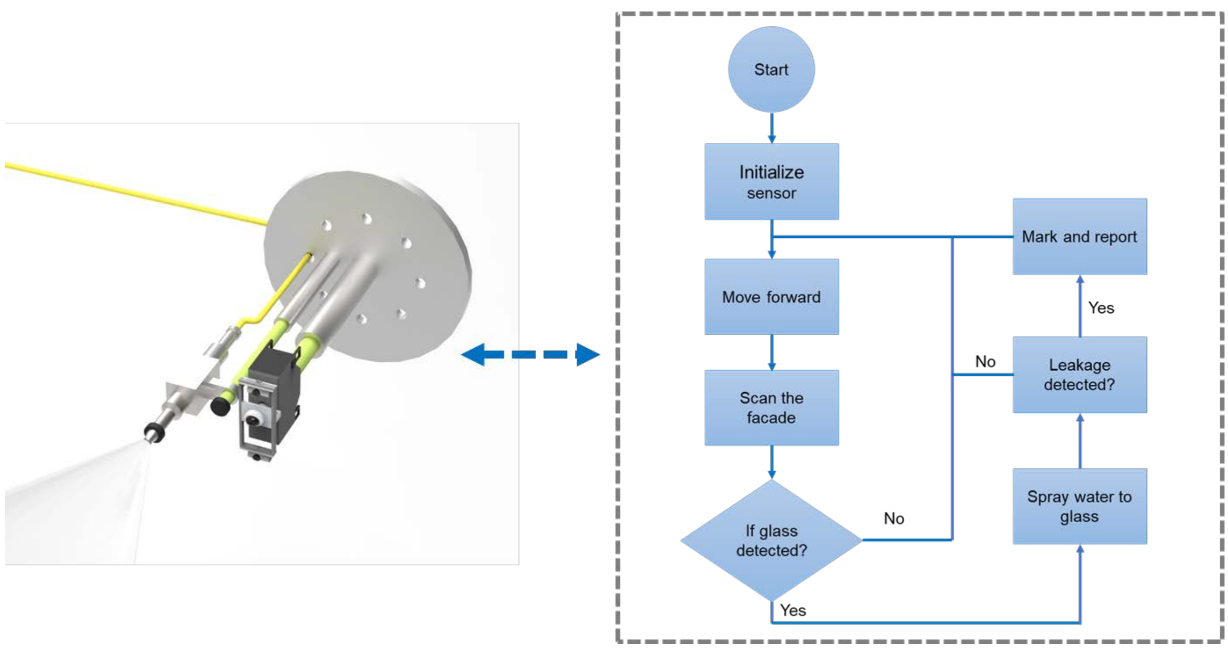


Figure 4-14: Leakage detection end-effector and its algorithm flowchart (the water leakage checking procedure is manually done by a worker inside of the target room using a thermal camera, see next page)

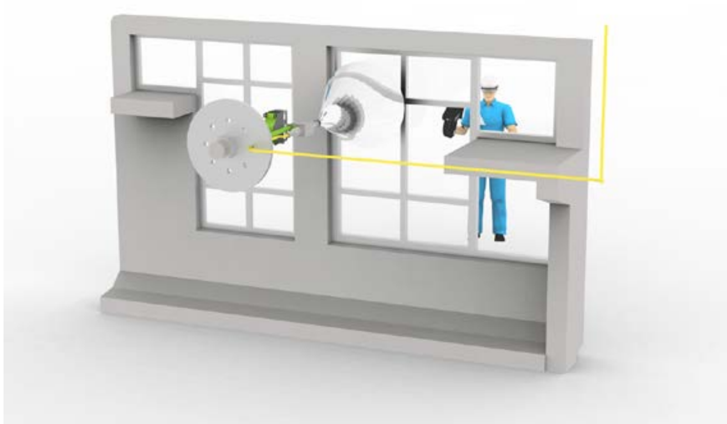


Figure 4-15: Leakage detection end-effector working scenario

(7) Fire extinguishing

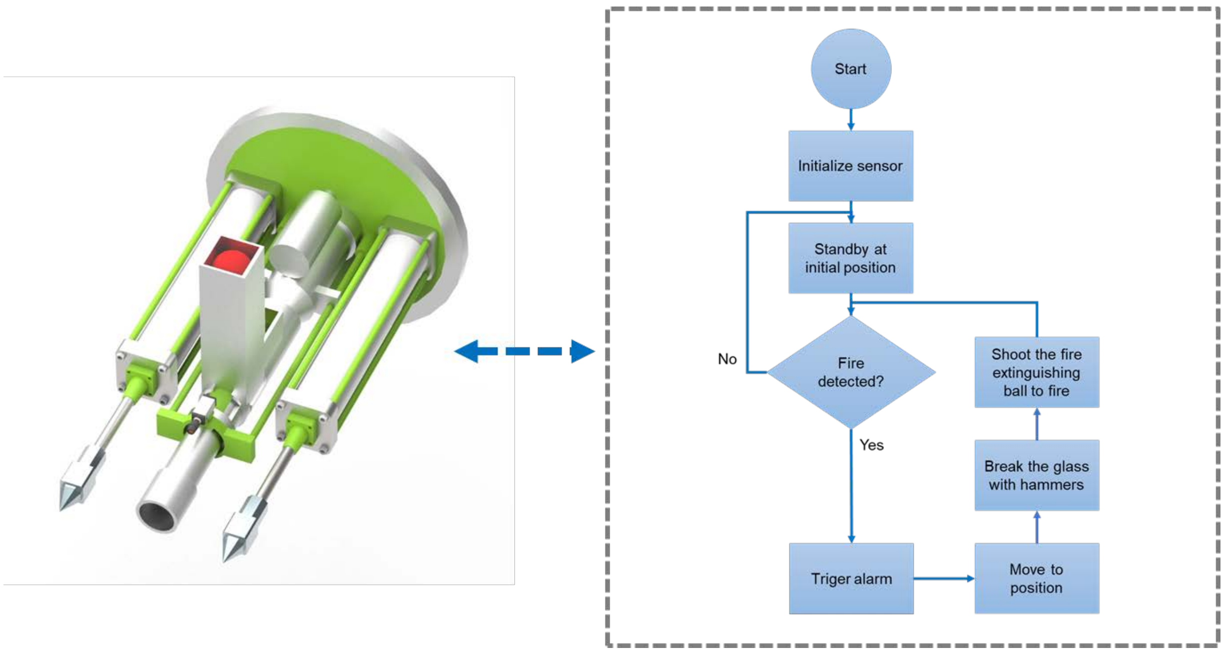


Figure 4-16: Fire extinguishing end-effector and its algorithm flowchart

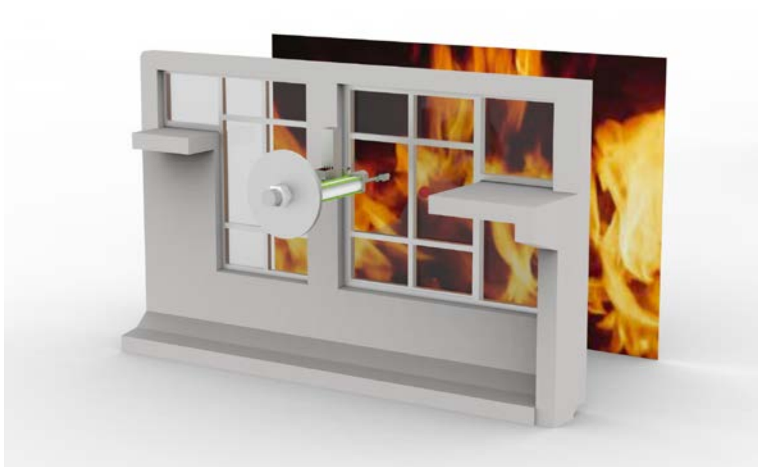


Figure 4-17: Fire extinguishing end-effector working scenario

(8) Façade installation and replacement

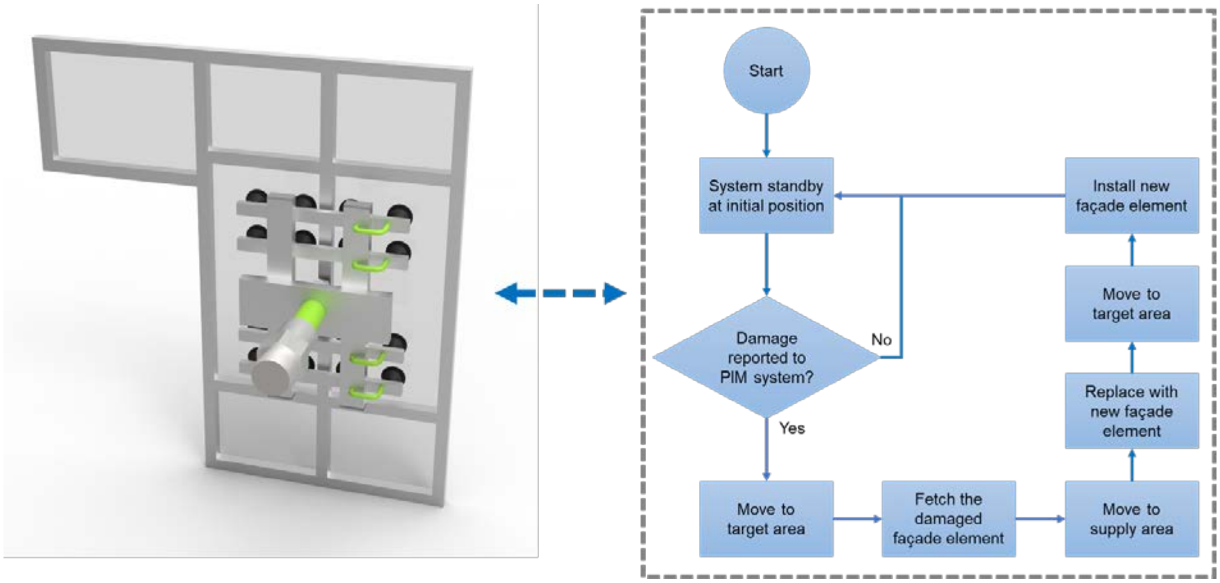


Figure 4-18: Façade installation and replacement end-effector and its algorithm flowchart

(9) Piping installation

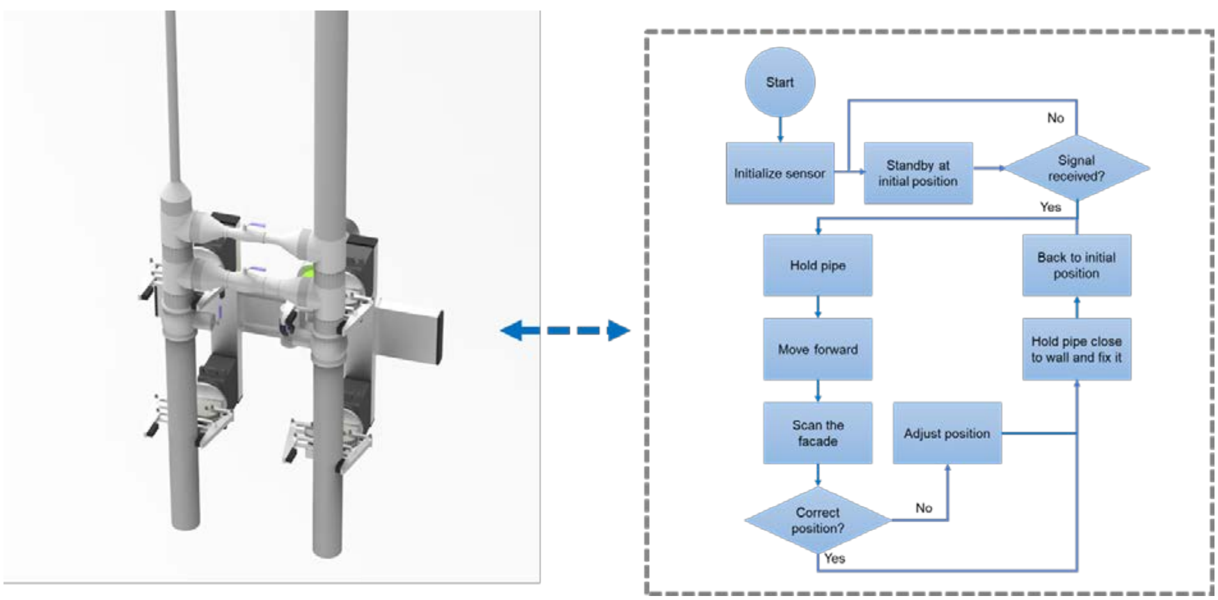
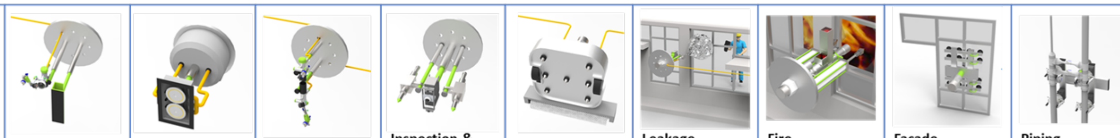


Figure 4-19: Piping installation end-effector and its algorithm flowchart

4.2.3 Building application scenarios

As mentioned earlier, the proposed robot system focuses on the façade tasks in Hong Kong Public Housing Construction (PHC) sector, these tasks include, but are not limited to exterior wall plastering, grinding, painting, inspection and marking, cleaning, leakage detection, fire extinguishing, façade installation and replacement, and piping installation. However, in order to further extend the types of potentially applied buildings and maximize the benefits of the proposed robot system, the application building types for these façade tasks can be broadened to office buildings, hotels, public / commercial buildings, factories, and shipyards. *Figure 4-20* shows a variety of building application scenarios where the identified façade tasks could be applied.

Various end-effectors for different façade tasks



Various building types	Fine plastering	Grinding	Painting	Inspection & marking	Cleaning	Leakage detection	Fire extinguishing	Façade installation	Piping installation
Public housing	●	●	●	●	●	●	●		●
Office				●	●	●	●	●	
Hotel	●	●	●	●	●	●	●	●	
Public & Commercial				●	●	●	●	●	
Factory	●	●	●	●	●	●			
Shipyard			●	●	●				

Figure 4-20: Application scenarios of the proposed façade tasks

4.3 Detailed positioning system

Positioning plays a significant role in a construction robot system. The proposed robot system might be affected by inertial forces and external forces when processing the façade tasks. If the robot is not fixed to the building, it might be moved unintentionally by these forces. In addition, the movement contains some errors related to control, measurement and so on. Therefore, a mechanism has been developed to fix the position to the building facade. In this section, the design and mechanism of the positioning system is demonstrated.

4.3.1 Proposed positioning end-effectors

In order to fix the robot to the appropriate position on the façade of public housing buildings in Hong Kong, the robot primarily has following end-effectors for positioning.
(1) Fine positioning system for horizontal positioning (see *Figure 4-21*, top right)
(2) Vacuum grippers for back and forth positioning (see *Figure 4-21*, bottom right)

The four vacuum grippers are designed to operate on any flat surface. They are also able to withstand wind loads under normal circumstances. The robot is not expected to operate in extreme situations such as strong wind and heavy rain.

The fine positioning system is designed only for adjusting the accuracy of the position. It is not meant to be used to withstand the wind loads. Therefore, pilot projects are needed to test the actual performance of the positioning system.

In addition, sudden strong wind might occasionally occur. Therefore, the TUM project team will need to develop a deliberate solution to tackle this stability issue in the follow-up projects.

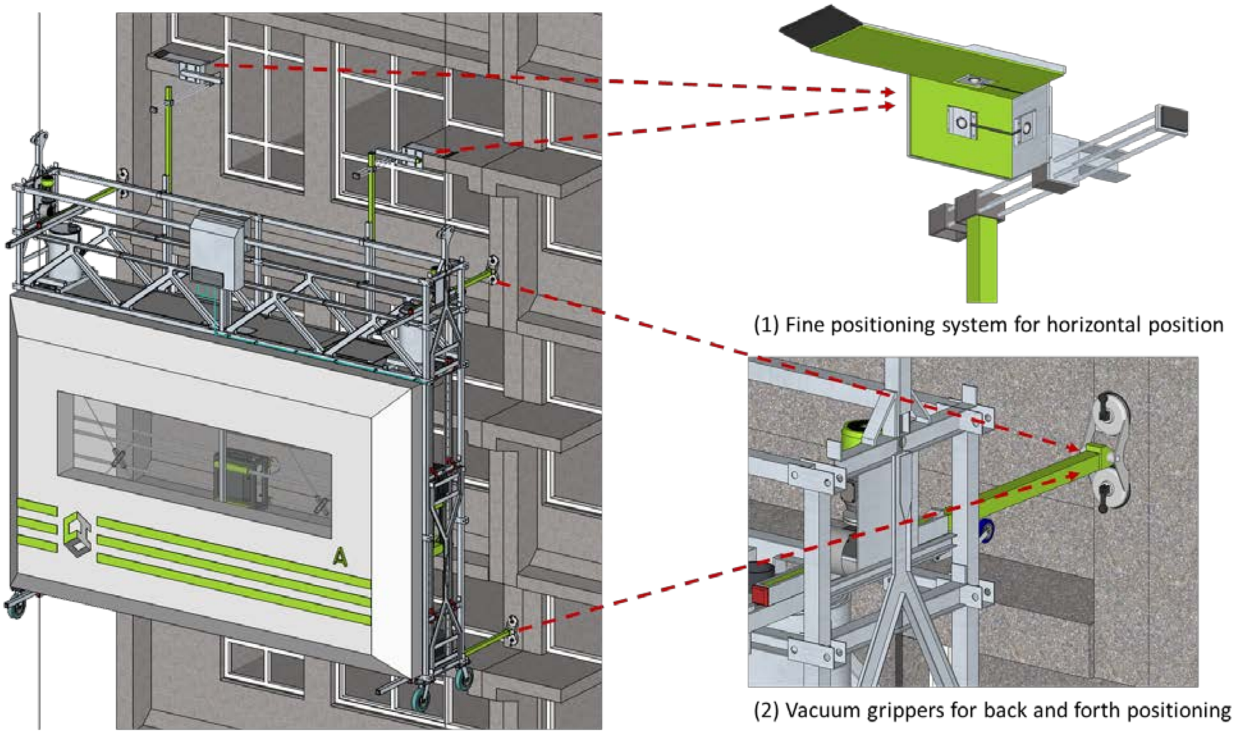


Figure 4-21: Proposed positioning end-effectors

Concerning other forms of movement, the vertical movement is virtually small and thus is negligible, because the ropes from the building roof hang the heavyweight robot. In addition, there is also an inevitable gap between the real position and the ideal one. The robot has a measurement function to calculate the gap using a camera.

4.3.2 Positioning process

The current positioning systems are especially designed to adapt to the public housing buildings in Hong Kong. The positioning system must be adjusted when applied to other types of buildings. Here is the description of each step of the positioning process.

(1) The 1st step

Robot descends along the ropes until the distance between the robot and overhangs becomes shorter than the preset threshold. The distance can be calculated with the initial position of the robot and the distance that the robot has moved. The moving distance can be calculated with pulley size of the motors and the number of motor revolutions (see *Figure 4-22*).

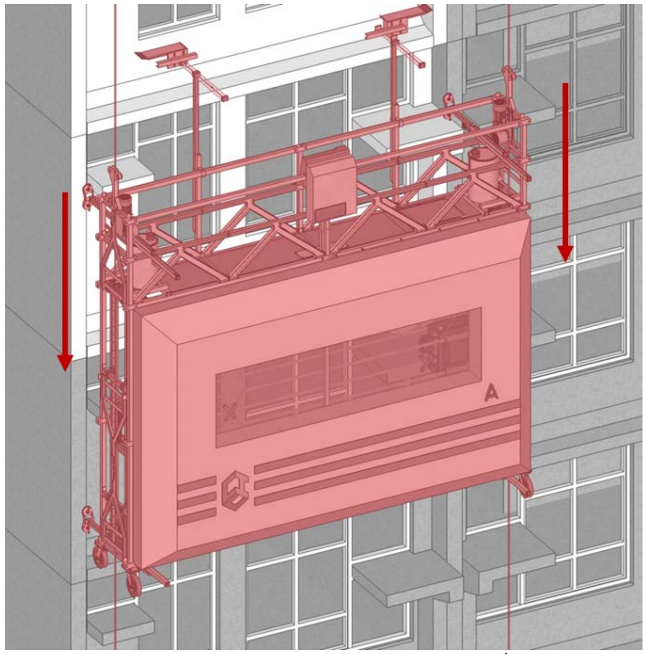


Figure 4-22: Positioning process – 1st step

(2) The 2nd step

The robot slows down the speed and descends until the force sensors on the fine positioning module detects the contact with the overhangs. After detection, the robot stops descending (see *Figure 4-23*). The detail of force sensing module is shown in *Figure 4-24*. When the force affects the module, the ball pushes the springs, then the force sensor on the base plate. Then this module detects the contact. Similar to the mechanism in the mechanical mouse, the ball can smoothly rotate on the contact surface. Its diameter is bigger than the hole diameter in the cover to prevent it from falling out.

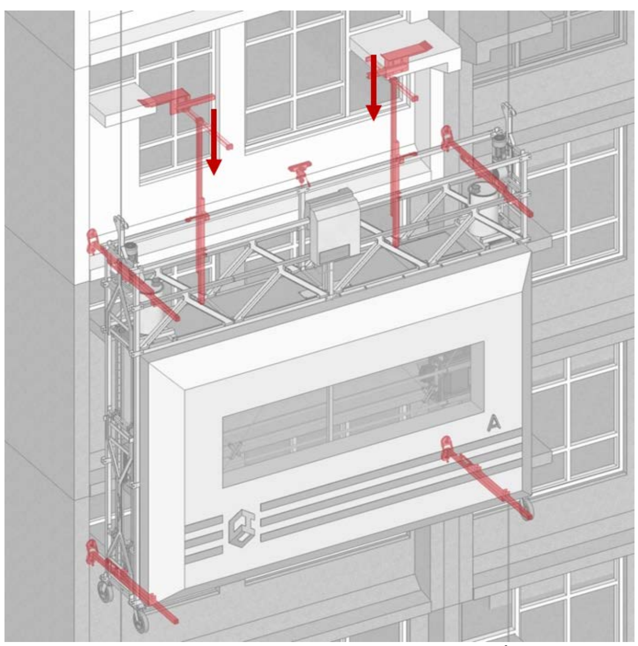


Figure 4-23: Positioning process – 2nd step

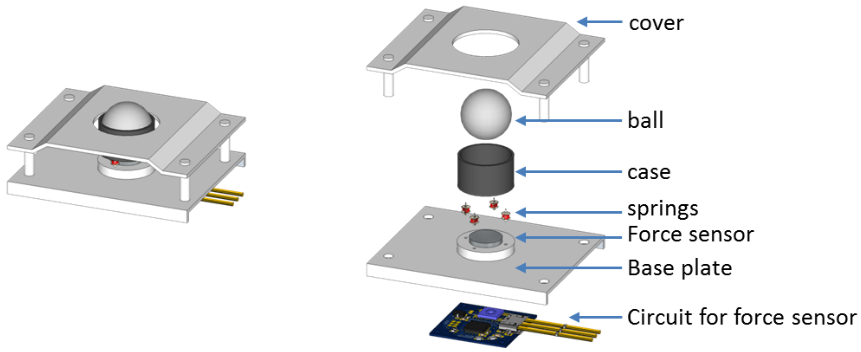


Figure 4-24: The mechanism of force sensing module (left: the overview of the module; right: the components of the module)

(3) The 3rd step

The robot moves the end-effector slowly to the wall along the X-axis. Same as the 2nd step, the robot stops the movement determined by the force sensing module (see *Figure 4-25*). The force module can slide on the overhang, because of its ball rolling mechanism.

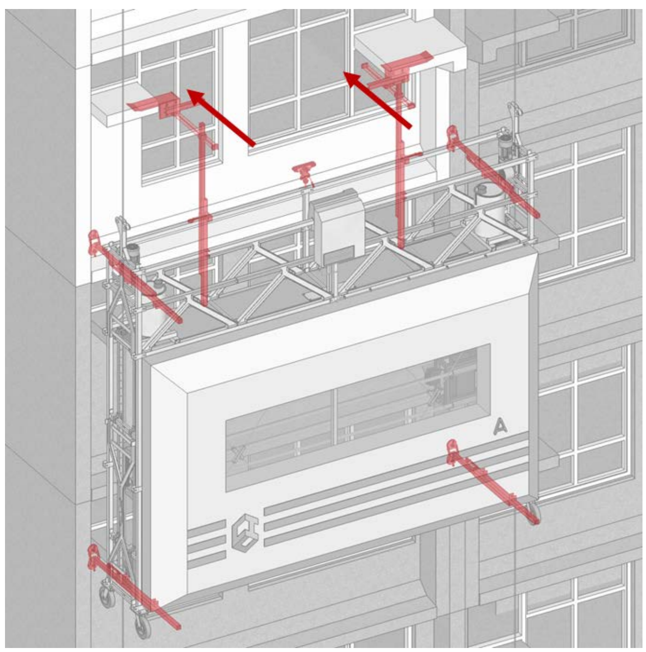


Figure 4-25: Positioning process – 3rd step

(4) The 4th step

The robot moves the end-effectors from the middle to the outside along the Y-axis (see *Figure 4-26*). The robot stops the movement like in the 2nd step and 3rd step. So far, if all three force sensors in the fine positioning module are affected by forces, the robot understands that it is in the right position to the overhangs. Incidentally, now the robot is fixed only to the overhangs. The positioning end-effectors may damage the overhangs by accident or vice versa. Therefore, the vacuum grippers are added to the robot system to further fix it to the wall.

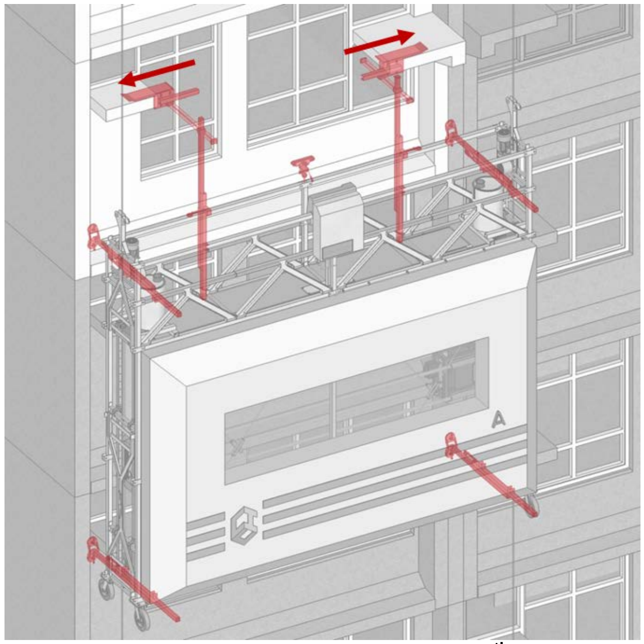


Figure 4-26: Positioning process – 4th step

(5) The 5th step

The robot extends the vacuum grippers toward the wall at the proper length, determined by the force sensors in the vacuum grippers. Then it grasps the wall to fix its position. Up to the 5th step, the robot can be fixed in position to the building. However, there could be a gap between the ideal position and the real one, because the building and the robot, respectively, have various errors such as measurement errors. The robot has to detect and analyze the gap (see *Figure 4-27*).

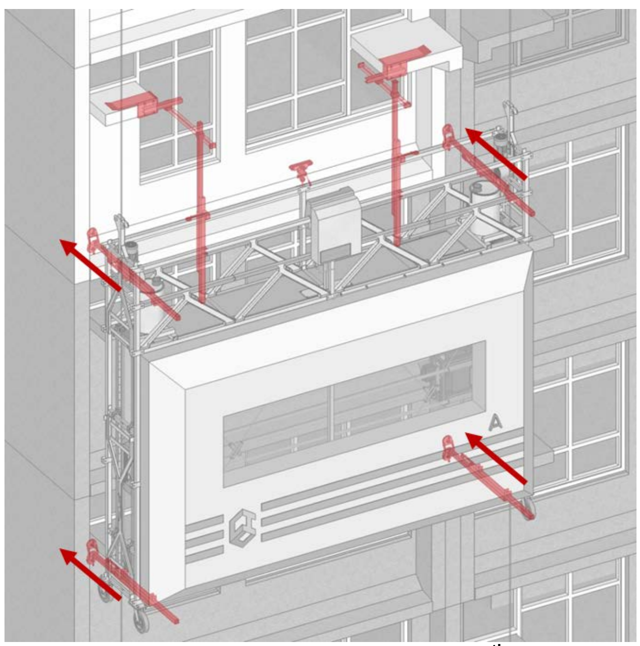


Figure 4-27: Positioning process – 5th step

(6) The 6th step

After, the robot calculates the deviation between the real position and the ideal one. Then the robot stores the deviation as an offset. The robot adjusts the end-effector movement with the deviation. It is calculated by comparing the building's 3D model and image by camera on the robot. If the deviation is larger than the threshold (for example, 5cm), then the robot repeats the positioning process from the 1st step. If after several times of repositioning the robot still cannot find the right position, an alarm will be triggered to notify the maintenance personnel to check the robot's condition on-site (see *Figure 4-28*).

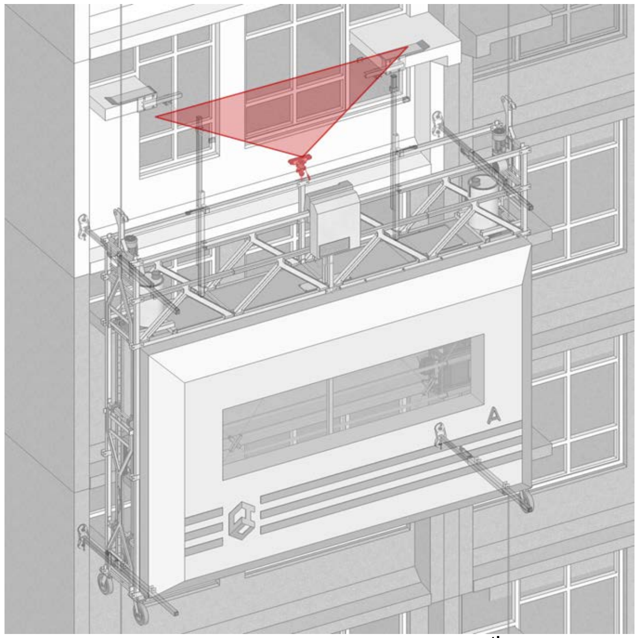


Figure 4-28: Positioning process – 6th step

4.4 Conclusions

Key insights and outcomes with regard to the technical detailing of the priority area "façade-processing" in this chapter:

1. The design of the proposed façade and exterior work robot system is revealed.
2. The changeable versatile plug-and-play end-effector system is introduced.
3. Three different modes of the robot to change the end-effector is proposed.
4. The various end-effectors and the applicable building types are proposed.
5. The positioning system of the robot is described and explained in detail.

5 Development of prototype (mock-up) of the façade-processing robot for demonstration and exhibition at CITAC

Based on the proposed façade/exterior work robot system demonstrated in *Chapter 4*, the project team has developed a prototype that demonstrates the design, kinematics, and functions of the façade processing robot system. In the next chapter, *Chapter 5*, the project team introduces the Process Information Modeling (PIM) concept, which can serve as the brain of the proposed robot system.

According to the agreement between CIC and TUM, a simplified 1:3 scale mock-up is built in collaboration with a robot company in Germany. The reasons that the mock-up is built in Germany instead of Shenzhen are threefold. First, it is easier for the TUM project team to communicate with a German company. Second, the quality control can be ensured due to close collaboration between TUM and the robot company. Third, the intellectual property of the proposed robot can be better protected. Furthermore, either the prototype or the mock-up would focus on only one task for simplification and budget reasons, and at the moment not the whole task/end-effector range that the project team has previously planned.

5.1 Prototype version (real size, fully functional; analyzed and cost calculated but not realized)

<u>Basic information about the conducted cost calculation:</u>

a) The cost estimation applies for one segment of the ring which can also be used as a standalone system
b) The cost estimation applies for a fully functional initial prototype
c) The cost estimation applies for the assembly of the system from medium-quality components in an economic way in a country like Germany
d) Cost were calculated by the leader of the chairs prototyping work shop, he has more than 20 years of experience in prototype building
e) Unit price estimations are based on 1) catalog prices, 2) request to companies, or 3) estimations based on experience.
f) Cost include taxes and shipping
g) The cost of the prototype (one of a kind product) are (as usual) significantly higher than the cost of a final commercially available system. For example, the purchase of the components in bulk will significantly bring down cost of material such as profiles and actuators. Furthermore, cost such as for the development of the controls system, programming of the controller, etc. can be distributed over all robots of the series later. Target cost for one segment (= standalone system) of a commercially available system shall be 50.000 – 80.000 € depending on the batch size.
h) All prices/cost are provided in Euros (€). Details can be seen from *Table 5-1* to *Table 5-5.*

Table 5-1: Cost position 1: Main Frame (aluminum carrier and accessories are all from the Maytec shelf)

Amount	Metric	Description	Unit Price	Total
60	meter	Basic frame profile 100x100 light version	59,95	4.280,43
50	meter	Stiffeners profile 50x50 light version	20,17	1.200,12
450	pieces	fasteners	3,99	2.136,65
5	pieces	Running gratings 1000x1000mm	188,00	940,00
2	pieces	Linear drives with control unit	ca. 2.500,00	5.000,00

1	pieces	Vacuum gripper with vacuum generator	ca. 4.500,00	4.500,00
		Small parts, rope tension, rolls, screws assembly material, delivery and shipping costs, etc.		5.000,00
30	hours	Detailed implementation planning (estimated)	150,00	4.500,00
		Total including 19% tax in €		**27557,20**

Note: Lengths and numbers are calculated respectively with 10% waste or reserve

Table 5-2: Cost position 2: Auxiliary and carrier frame for the painting unit:

Amount	Metric	Description	Unit Price	Total
40	meter	Running profile 100x50	35,38	1.684,01
20	meter	Stabilization braces 50x50	20,17	480,01
150	pieces	Fasteners	3,99	712,22
50	pieces	Angle elements 50x50	5.48	326,06
40	pieces	Linear guides & running elements	9,85	468,86
		Small parts, rope tension, rolls, screws assembly material, delivery and shipping costs, etc.		5.000,00
30	hours	Detailed implementation planning (estimated)	150,00	4.500,00
		Total including 19% tax in €		13.171,16

Note: Lengths and numbers are calculated respectively with 10% waste or reserve

Table 5-3: Cost position 3: Control system and actuators

Amount	Metric	Description	Unit Price	Total
4	pieces	Linear actuators (sub-frame paint spraying console)	ca. 5.000,00	20.000,00
2	pieces	Linear drives (frames and paint spraying elements)	ca. 2.500,00	5.000,00
8	pieces	Axial drives (paint spraying elements)	1.527,16	12.217,28
50	pieces	Sensors for end positions and dependencies	117,81	5.890,5
10	pieces	Emergency and local switch for direct operation	50,00	500,00
1	pieces	Control panel (operating unit)	4.837,23	4.837,23
1	pieces	Main control unit	9.000,00	9.000,00
1	pieces	Cables and wires	15.000,00	15.000,00
50	pieces	Plug and connection elements	100,00	5.000,00
20	pieces	Mechanical holders, adapters and couplings	300,00	6.000,00
100	hours	Programming and adjustment of the controller	150,00	15.000,00
150	hours	Assembly, adjustment, cabling, commissioning of the control and troubleshooting	150,00	22.500,00
150	hours	Detailed implementation planning (estimated)	150,00	22.500,00
		Total including 19% tax in €		**143445,01**

Table 5-4: Cost position 4: Spray painting equipment

Amount	Metric	Description	Unit Price	Total
1	pieces	Paint sprayer with 4 as a complete unit by the company Nordson http://www.nordson.com/de-DE/divisions/industrial-coating-systems/products/spray-systems/trilogy-air-spray-as-and-low-volume-low-pressure-lvlp-manual	35.000,00	35.000,00
		Total including 19% tax in €		35.000,00

Table 5-5: Summary cost estimated for "one of a kind" prototype

CP1	Main Frame	27.557,20
CP2	Auxiliary and carrier frame for the painting unit	13.171,16
CP3	Control system and actuators	143.445,01

CP4	Spray painting equipment	35.000,00
	Total in €	**219.173,37**

A more sophisticated prototype towards market application may also consider cost positions for the following:

- When working with paints and varnishes or ignitable color dusts, it is important to notice that a local EXX area might be useful and working with IP68EX requires more expensive components and cables of the electrical system.
- The system has to be made weather proof
- Consider work safety aspects (parapet height of the work platform, belt guide, etc.)

5.2 Mock-up version (1:3 scale, simplified functions; realized due to budget reasons)

Table 5-6: The cost breakdown of the 1:3 scale simplified mock-up

Name	Total price

1:3 mock-up
• Frame:
  o 40X40 Profiles
  o Connections and lightweight cover
  o Similar to sketch of TUM
• Linear guide:
  o 3 axes linear guidance
  o Engine and gearboxes
• Control system:
  o AMK on codesys
• Control panel:
  o The supplied panel can be placed approx. 3-4 meters away
  o From there the whole operation can take place
  o Touch panel with different buttons, automatic start / stop, hand X, Y and Z, settings etc.
• Pointer:
  o As a demo for the spray head
	31.500,00

Total including 19% tax in €	37.485,00

5.3 Overall description of the mock-up design

The mock-up has movability in 3 axes, which simulates the aforementioned proposed robot system (see *Figure 5-1*). The project team decided to build it in a 1:3 scale, and the detailed dimensions can be seen in *Figure 5-2*. Among other things, the mock-up will be built on a modular and extendible platform, so that later on the project team could expand this mock-up with additional motors, axes, and functions after the final presentation (when there are additional resources). Eventually, it will become a small research platform as well.

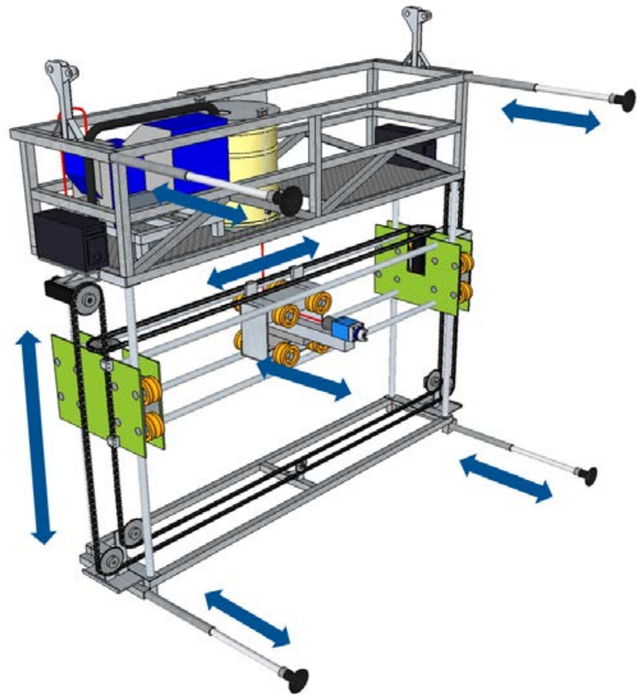


Figure 5-1: Overall design of the 1:3 scale mock-up showing its movability

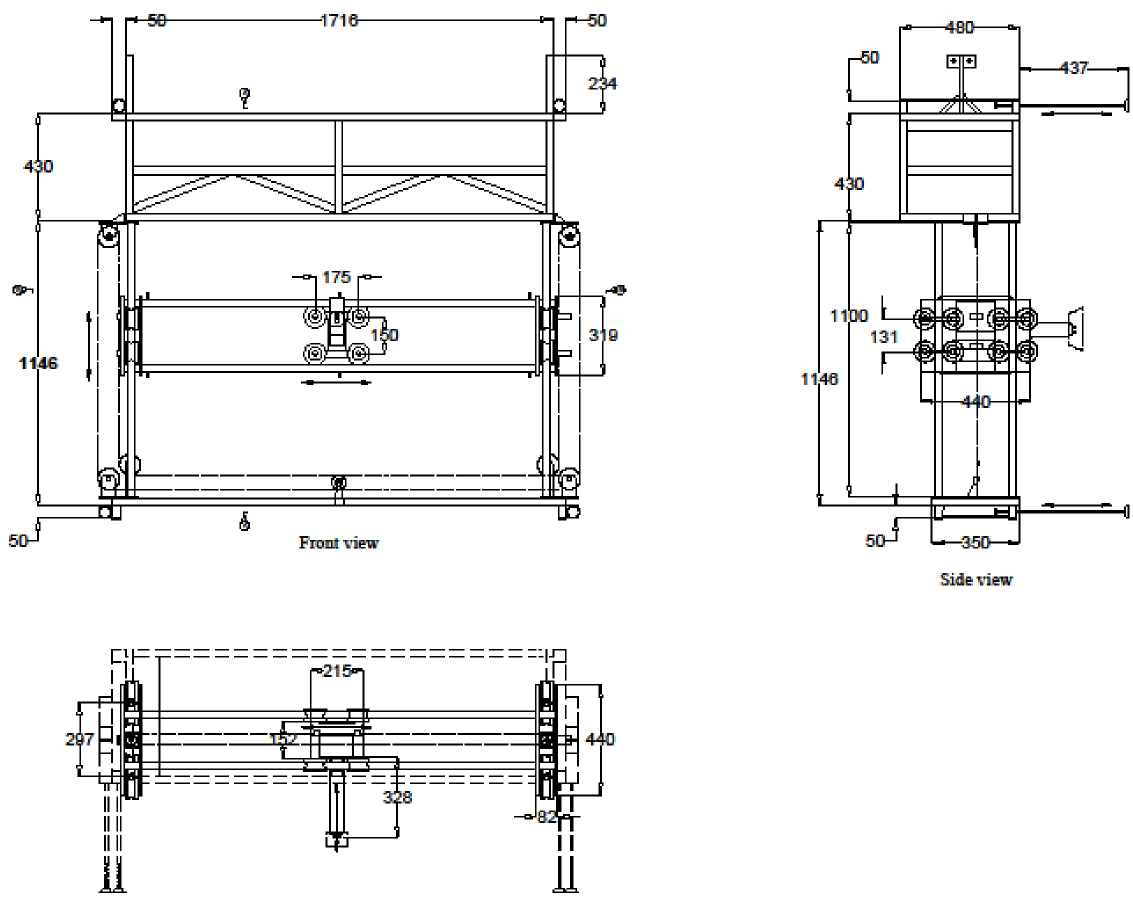


Figure 5-2: Detailed dimensions of the proposed mock-up design (unit in mm)

In addition, a lightweight cover can be added to the mock-up to further protect it in terms of dust, water, shock, and confidentiality (see *Figure 5-3*).

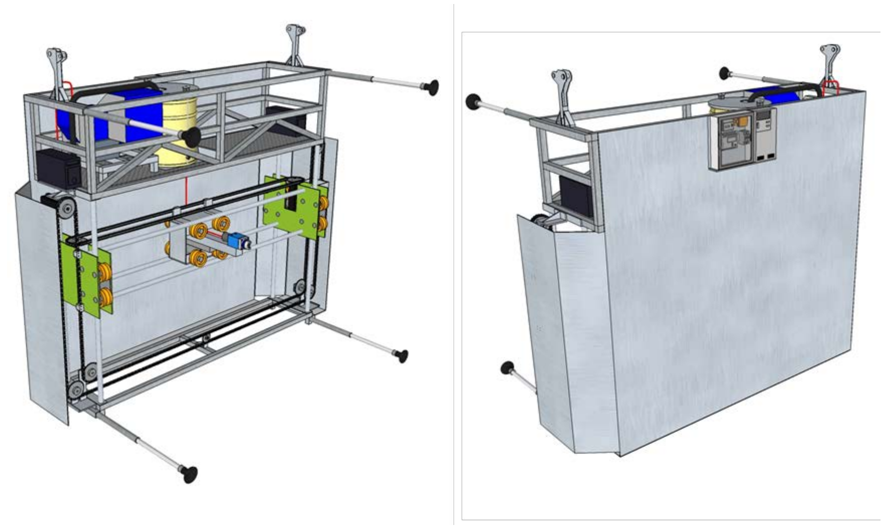


Figure 5-3: An optional cover for the mock-up might be needed to further protect the mock-up

5.4 Detailed description of the mock-up components

As shown in *Figure 5-4*, the proposed design of the mock-up consists of 14 main components. These include a suspended working platform, hoisting devices, travel tubes, track roller wheels, drive chain, chain gear devices, servomotors, a power supply, an automated spray gun, an airless paint sprayer, a paint bucket, a control unit, compressed air suction cup stabilizers, and a linear actuator. The function and selection of each component will be described in detail as follows.

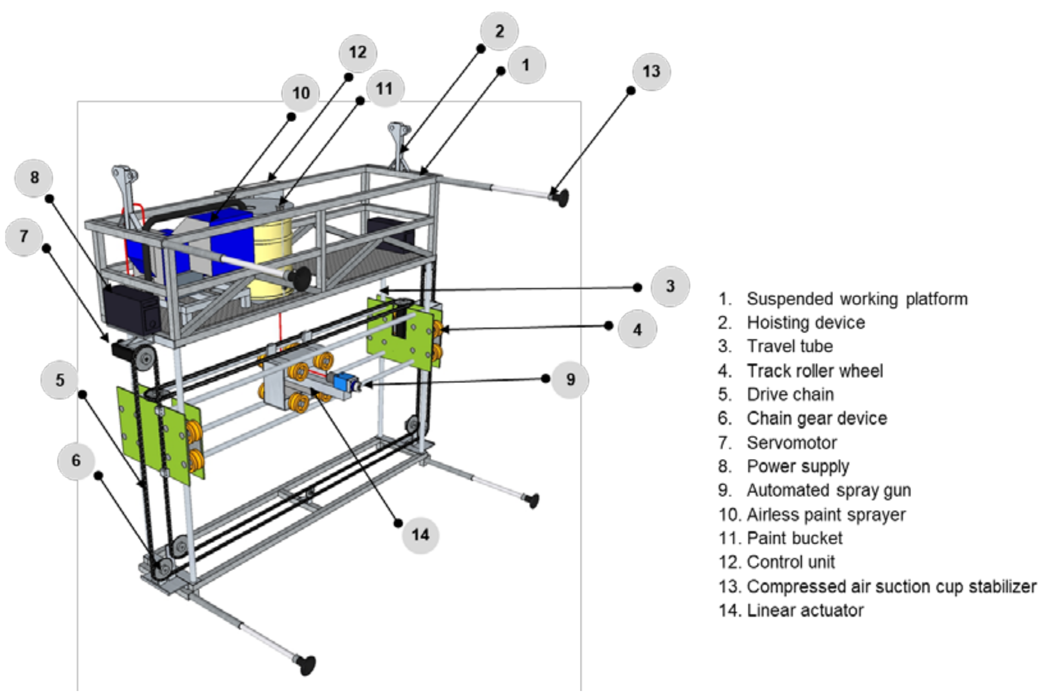


Figure 5-4: Detailed explanation of the mock-up

(1) <u>Suspended working platform</u>

The design of proposed robot system is based on a suspended working platform. As the main frame of the mock-up, the suspended working platform (see example in *Figure 5-5*) can be made from aluminum profiles (i.e., the 40mm x 40mm type). The profile system is easy to process and quick to assemble. Its flexible and modular construction means that it can be easily modified and is reusable at any time. A wide range of accessories provides functional and aesthetic results to applications (see *Figure 5-6*).

Figure 5-5: Example of a suspended working platform

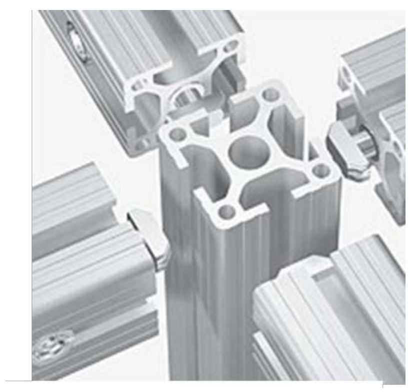


Figure 5-6: Section of the aluminum profile

(2) Hoisting device

Existing hoisting hangers from a working platform can be adapted and used in the mock-up. The project team can also improvise and build a simple device with the similar function (see example in *Figure 5-7*).

Figure 5-7: Example of a hoisting hanger

(3) <u>Travel tube</u>

Commonly seen in a 3D printer, the travel tube is the key component in a linear movement. The material for the travel tube can be made of tube aluminum profiles (see *Figure 5-8*).

Figure 5-8: Example of metal travel tube

(4) <u>Track roller wheel</u>

The material for the track roller wheel can be rubber, plastic or steel. The actual material and dimension of the wheels need to be confirmed with the engineers from the material provider (see example in *Figure 5-9*).

Figure 5-9: Example of various track roller wheels

(5) <u>Drive chain</u>

Chain drive is a way of transmitting mechanical power from one place to another. Although commonly seen in bicycles and motorcycles, it is widely used in a variety of machines besides vehicles. It is a suitable mechanism for the mock-up because of its durability and affordability. The dimensions of the chains need to be confirmed with the engineers from the supply company (see *Figure 5-10*).

Figure 5-10: Example of the drive chain

(6) <u>Chain gear device</u>

The chain gears in the mock-up need to be durable. The dimensions and material of the chain gear need to be confirmed with the engineers from the supply company (see *Figure 5-11*).

Figure 5-11: Example of the chain gear device

(7) <u>Servomotor</u>

A servomotor refers to a rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity and acceleration. It consists of a suitable motor coupled to a sensor for position feedback. It also requires a relatively sophisticated controller, often a dedicated module designed specifically for use with servomotors. The proposed mock-up design requires two servomotors, of which the specifications need to be confirmed with the automation company (see *Figure 5-12*).

Figure 5-12: Example of the servomotor

(8) Power supply

The specifications of the power supply, which is based on the selection of the servo and linear motors, need to be confirmed with the automation company. *Figure 5-13* is an example of the possible power supply.

Figure 5-13: Example of the power supply

(9) Automated spray gun

The automated spray gun is a key component in the mock-up as well as the actual robot system. For instance, the Automatic airless spray gun (see *Figure 5-14*) can be considered for the reasons below:

- Lightweight and compact rounded gun design
- Capable of handling high production speeds
- Durable stainless steel construction handles the toughest materials
- Fewer parts means an overall lower cost of maintenance or repair
- Wide range tip line for a variety of applications

Figure 5-14: The Automatic Airless Spray Gun

(10) Airless paint sprayer

Airless paint sprayers on the market can be used to build this mock-up. For example, *Figure 5-15* shows the a kind of Airless Electric Sprayer.

Figure 5-15: Airless Electric Sprayer

(11) <u>Paint bucket</u>

A paint bucket needs to be built which can be refilled, cleaned, and securely fixed, see the design in *Figure 5-16*. Alternatively, Hopper kit can be adapted and used in the proposed system (see *Figure 5-17*).

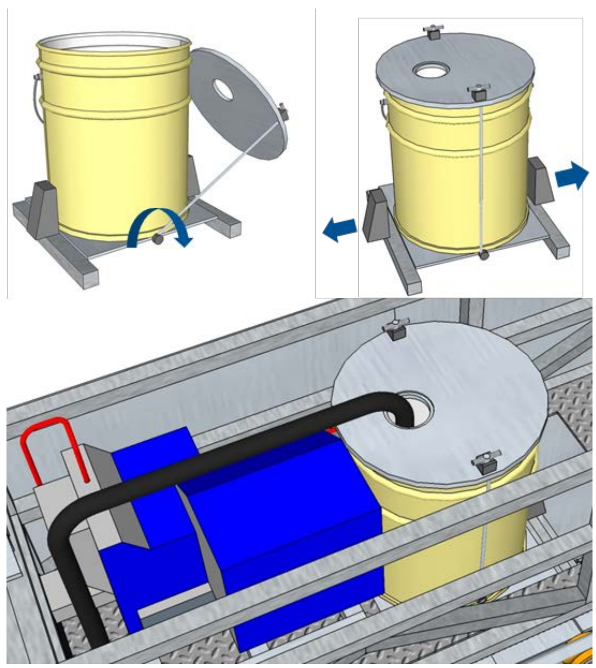
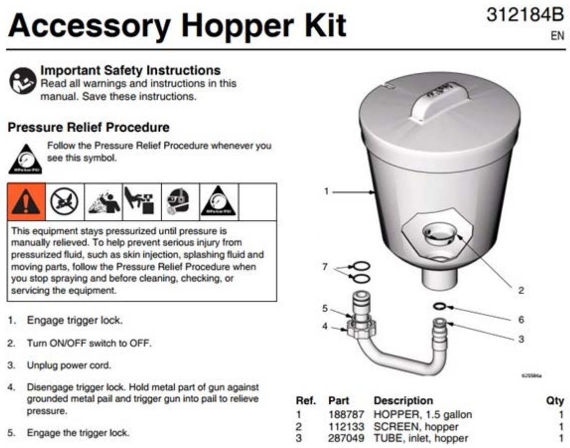


Figure 5-16: Proposed paint bucket design



Accessory Hopper Kit

312184B
EN

Important Safety Instructions
Read all warnings and instructions in this manual. Save these instructions.

Pressure Relief Procedure

Follow the Pressure Relief Procedure whenever you see this symbol.

This equipment stays pressurized until pressure is manually relieved. To help prevent serious injury from pressurized fluid, such as skin injection, splashing fluid and moving parts, follow the Pressure Relief Procedure when you stop spraying and before cleaning, checking, or servicing the equipment.

1. Engage trigger lock.
2. Turn ON/OFF switch to OFF.
3. Unplug power cord.
4. Disengage trigger lock. Hold metal part of gun against grounded metal pail and trigger gun into pail to relieve pressure.
5. Engage the trigger lock.

Ref.	Part	Description	Qty
1	188787	HOPPER, 1.5 gallon	1
2	112133	SCREEN, hopper	1
3	287049	TUBE, inlet, hopper	1

Figure 5-17: Technical details of the Hopper kit as the paint supply vessel

(12) <u>Control unit</u>

The project team needs to consult the automation company what kind of control unit is needed for the design concept. This also depends on the degree of automation and the sensors the robot will equip (see *Figure 5-18*).

Figure 5-18: Example of the control unit

(13) <u>Compressed air suction cup stabilizer</u>

Four sets of compressed air suction cups need to be used as the stabilizers for the robot in order to achieve the proper load bearing for the robot (see *Figure 5-19*). The stabilizing system usually consists of:

- Suction cups
- Fastening elements of the vacuum cups
- Vacuum generation (rotary vane vacuum pumps which is oil-lubricated)
- Possibly other accessories, which need to be confirmed with the automation company

Figure 5-19: Example of the compressed air suction cup stabilizer

(14) <u>Linear actuator</u>

One set of linear actuator is needed where the automatic spray gun will be fixed. The specification and control system of the linear actuator need to be confirmed by the automation company. *Figure 5-20* indicates a few examples of the possible linear actuators.

Figure 5-20: Examples of the linear actuators

(15) <u>Sensors</u>

Sensors play an important role in robot systems. Particularly in this mock-up, proximity sensor, which is a sensor for detecting the presence of nearby objects without any physical contact, will be needed to avoid collision between the robot and the facade (see examples in *Figure 5-21*). The detail needs to be discussed and confirmed with the automation company.

Figure 5-21: Proximity sensors

(16) <u>Joystick control box</u>

A joystick is an input device consisting of a stick that pivots on a base and reports its angle or direction to the device it is controlling. The joystick control box for the mock-up needs to be user-friendly and easy to operate. Perhaps the speed control function can also be added to this control box. *Figure 5-22* shows the design of the control box and *Figure 5-23* is a study mock-up of it.

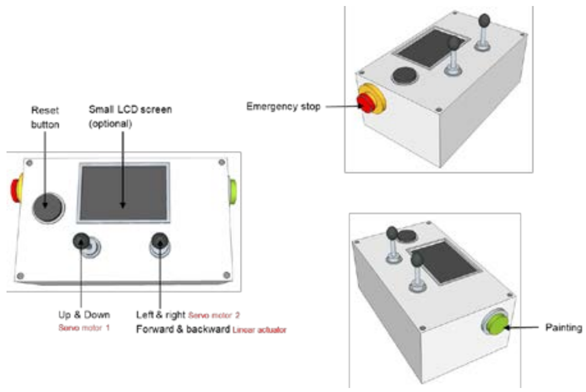


Figure 5-22: Proposed design of the joystick control box

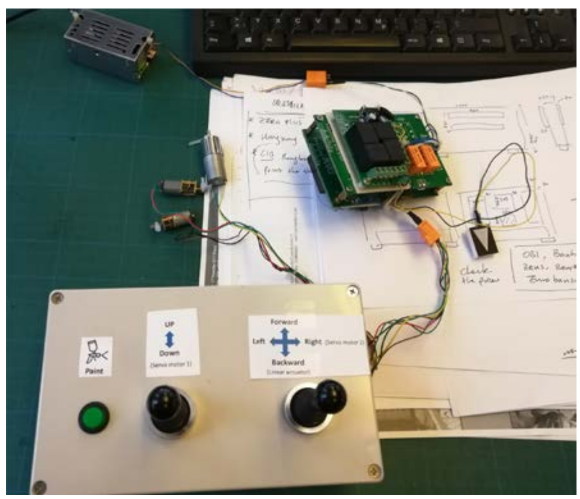


Figure 5-23: Mock-up of the joystick control box

5.5 Manufacturing the final version of the mock-up

As previously mentioned, the final version of the mock-up is manufactured in collaboration with TUM's technical partner, HERO GmbH **(HERO GmbH, 2018)**. The TUM project team traveled to HERO GmbH several times in order to ensure the progress and quality of the mock-up manufacturing. The overall process of building the mock-up was smooth and successful. *Figure 5-24* to *Figure 5-35* illustrate the details of the mock-up.

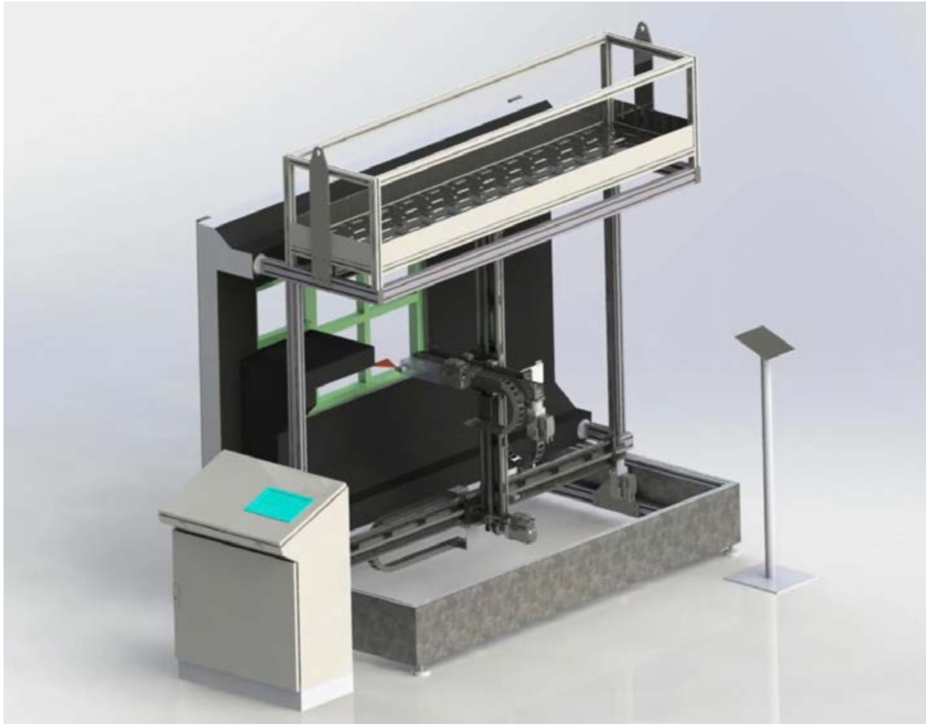


Figure 5-24: Final visualization of the whole system (Image: HERO GmbH)

Figure 5-25: Completed mock-up in HERO GmbH facilities

Figure 5-26: Control station with advanced control technology

Figure 5-27: Circuit inside of the control station

Figure 5-28: User interface of the power supply

Figure 5-29: Friendly user interface in both English and German

Figure 5-30: Gondola working platform on top of the robot

Figure 5-31: Suction cup for stabilizing the mock-up

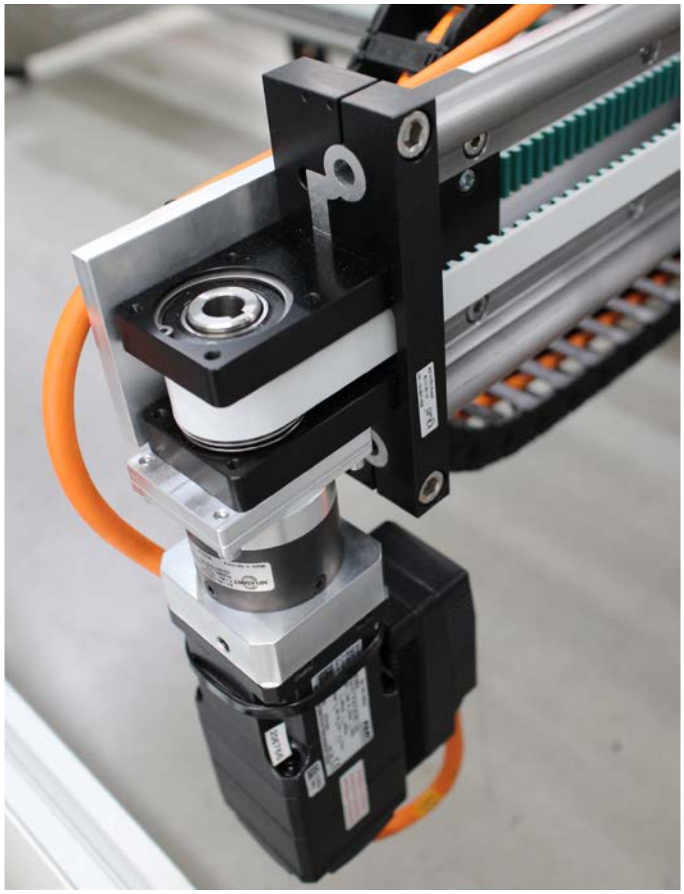


Figure 5-32: Detail of the motor

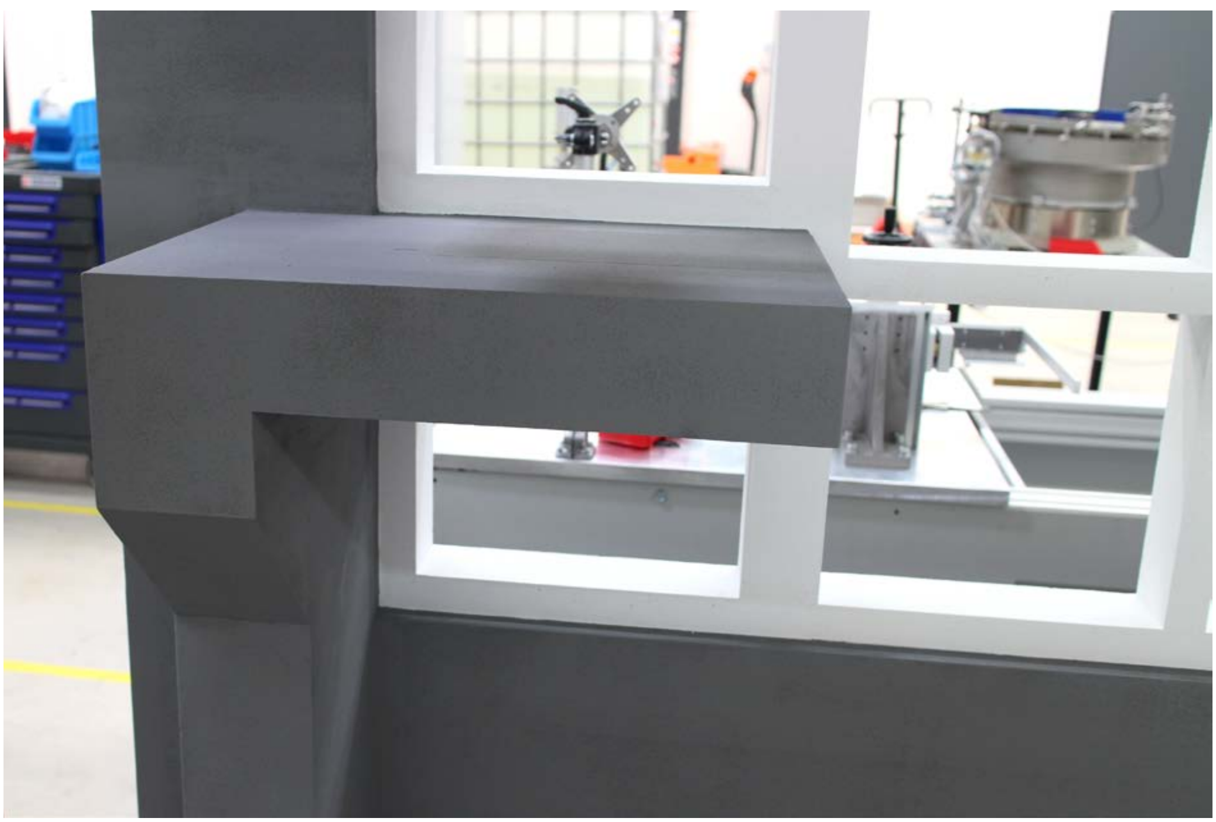


Figure 5-33: Detail of the mock-up wall

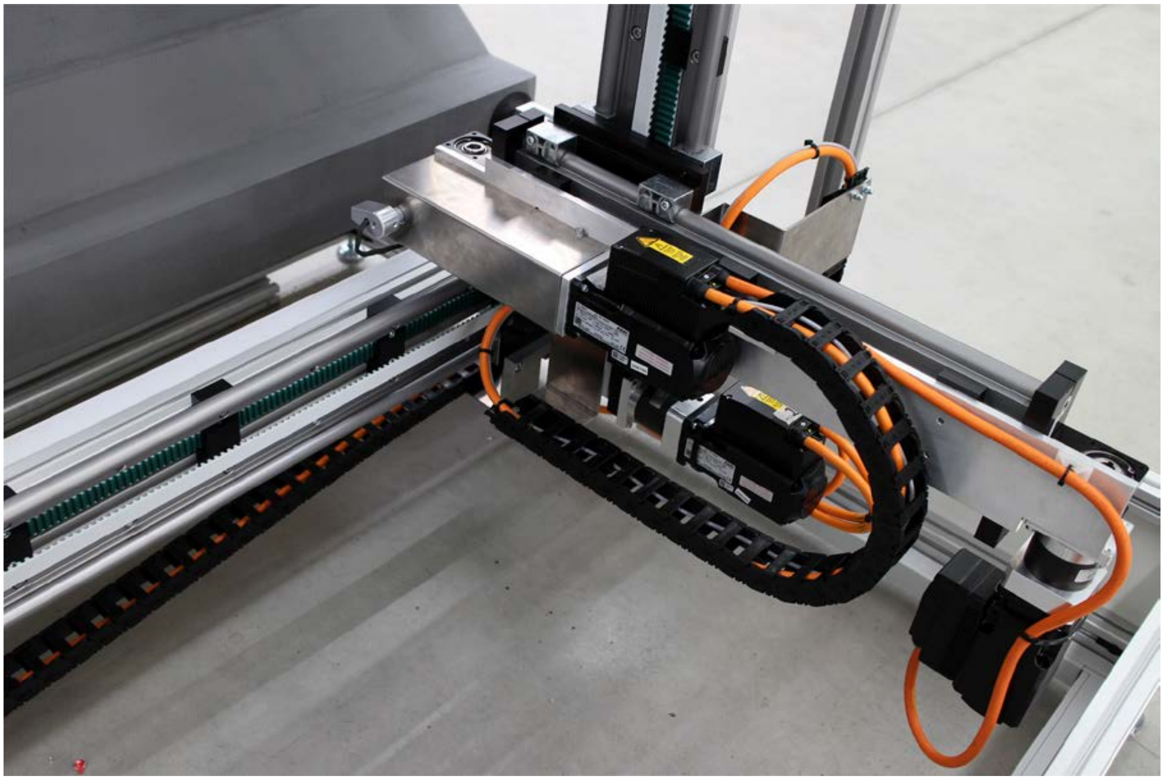
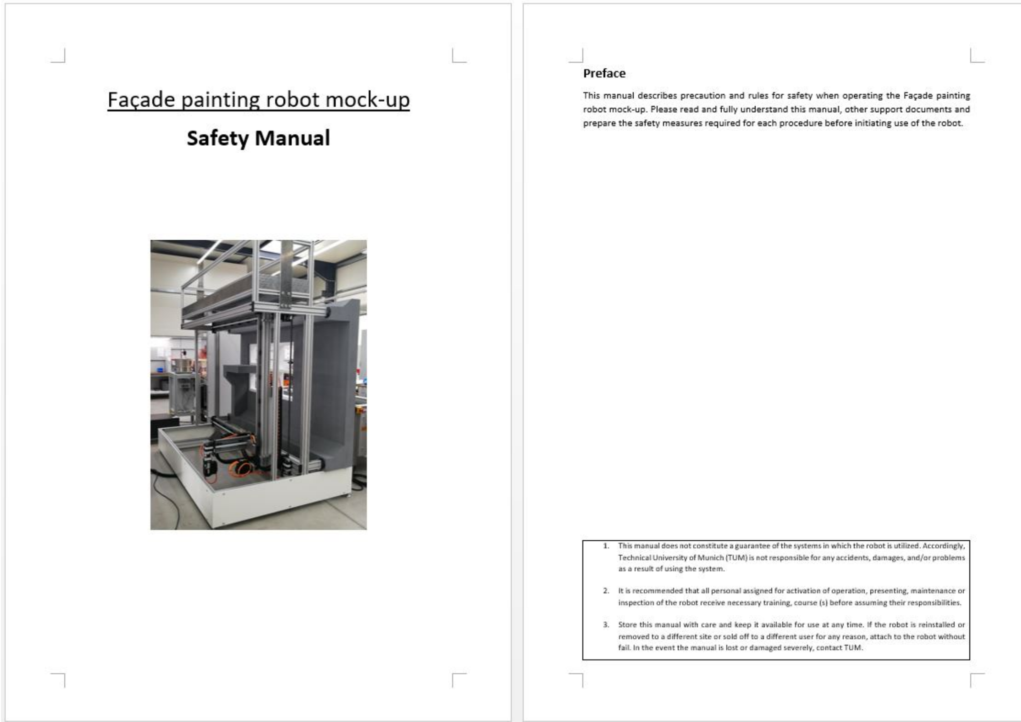


Figure 5-34: Flexible robotic manipulator supported by linear movements

Figure 5-35: Painting process demonstration simulated by laser end-effector

In addition, the TUM project team together with HERO GmbH produced a safety manual for installing, operating, and maintaining the mock-up at the exhibition center (in a separate file, see *Figure 5-36*). As a result, technicians in the exhibition center can easily configure the circuit and set up the mock-up system following the safety manual (see *Figure 5-37*). Afterwards, the mock-up will be packed and shipped to Hong Kong by a professional shipping company for exhibition and demonstration purposes.



Façade painting robot mock-up

Safety Manual

Preface

This manual describes precaution and rules for safety when operating the Façade painting robot mock-up. Please read and fully understand this manual, other support documents and prepare the safety measures required for each procedure before initiating use of the robot.

1. This manual does not constitute a guarantee of the systems in which the robot is utilized. Accordingly, Technical University of Munich (TUM) is not responsible for any accidents, damages, and/or problems as a result of using the system.
2. It is recommended that all personal assigned for activation of operation, presenting, maintenance or inspection of the robot receive necessary training, course (s) before assuming their responsibilities.
3. Store this manual with care and keep it available for use at any time. If the robot is reinstalled or removed to a different site or sold off to a different user for any reason, attach to the robot without fail. In the event the manual is lost or damaged severely, contact TUM.

Figure 5-36: Cover page of the safety manual (draft)

Figure 5-37: Setting up the mock-up system following the safety manual

5.6 Demonstration and exhibition of the robotic mock-up at CITAC

Eventually, the mock-up is expected to be displayed and demonstrated to the public in the Construction Innovation and Technology Application Centre of Hong Kong (CITAC). The proposed location for placing the mock-up is shown in *Figure 5-38* and the maximum dimension of the setup (2300mm*900mm*2500mm) that can be used is shown in *Figure 5-39*.

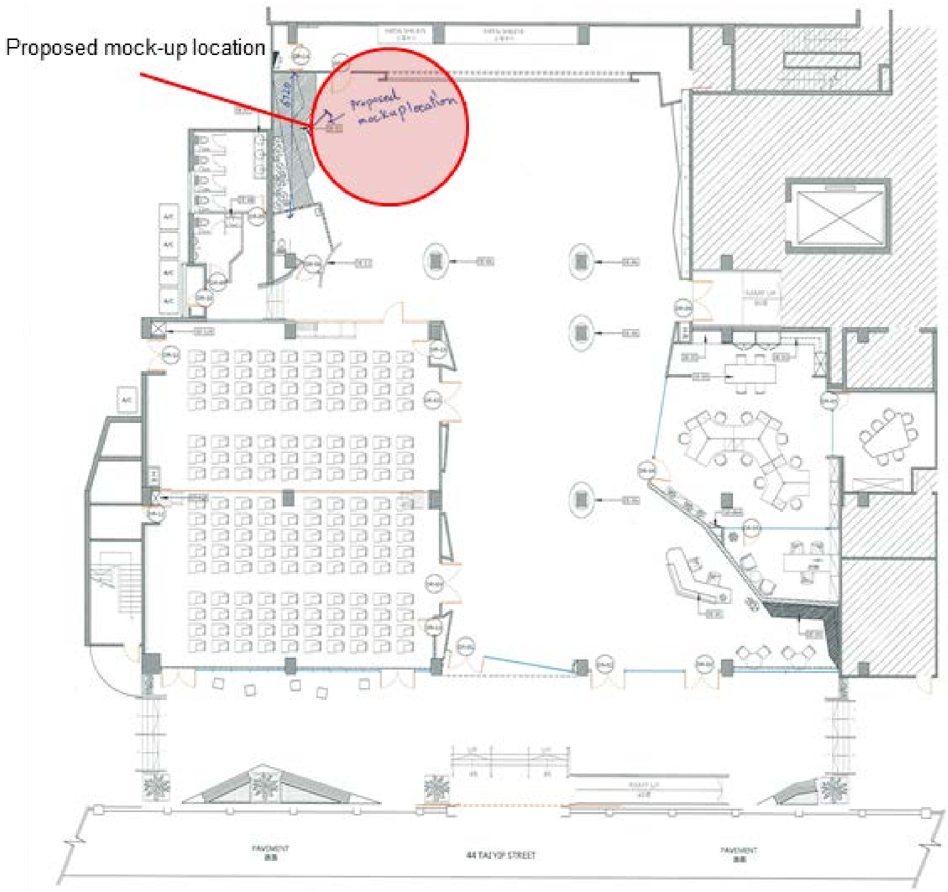


Figure 5-38: Floor plan of CITAC with mock-up display location indicated

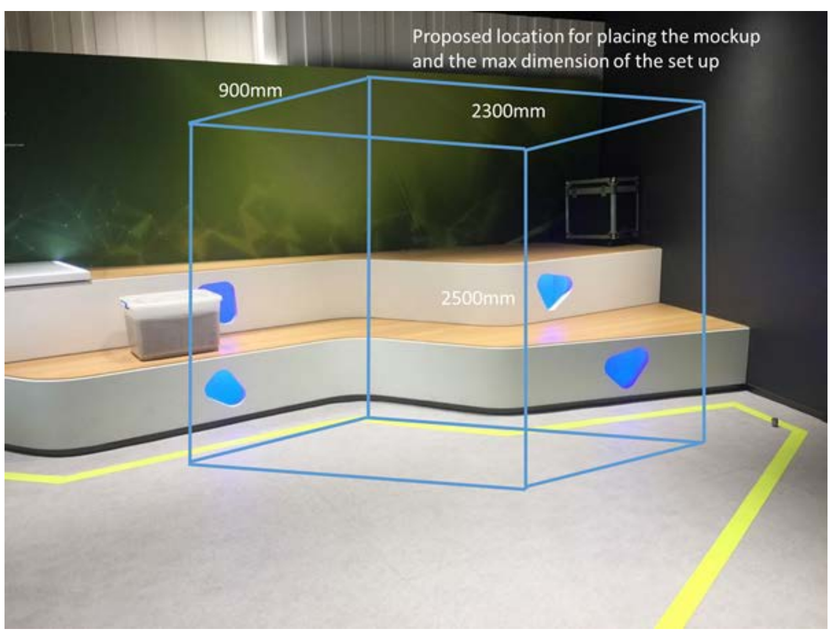


Figure 5-39: Proposed location for placing the mock-up

The project is running under a strict timeline and an exceedingly tight budget. Therefore, it was decided that a demonstration mock-up in the scale of 1:3 should be built to demonstrate the main functions. In addition, small changes to the final design were made to achieve a more cost-effective mock-up. For example, instead of the chain gear and an airless paint sprayer, some linear systems and a laser pointer are used in the demonstration. All these changes imply a good communication between TUM and the prototype manufacturer Hero GmbH. A scale model of the wall helps to better demonstrate the working procedure of the mock-up. The mock-up is controlled by a control panel, which can be placed up to 3-4m away from the mock-up. A presumptive visualization in CITAC exhibition area can be seen in *Figure 5-40*.

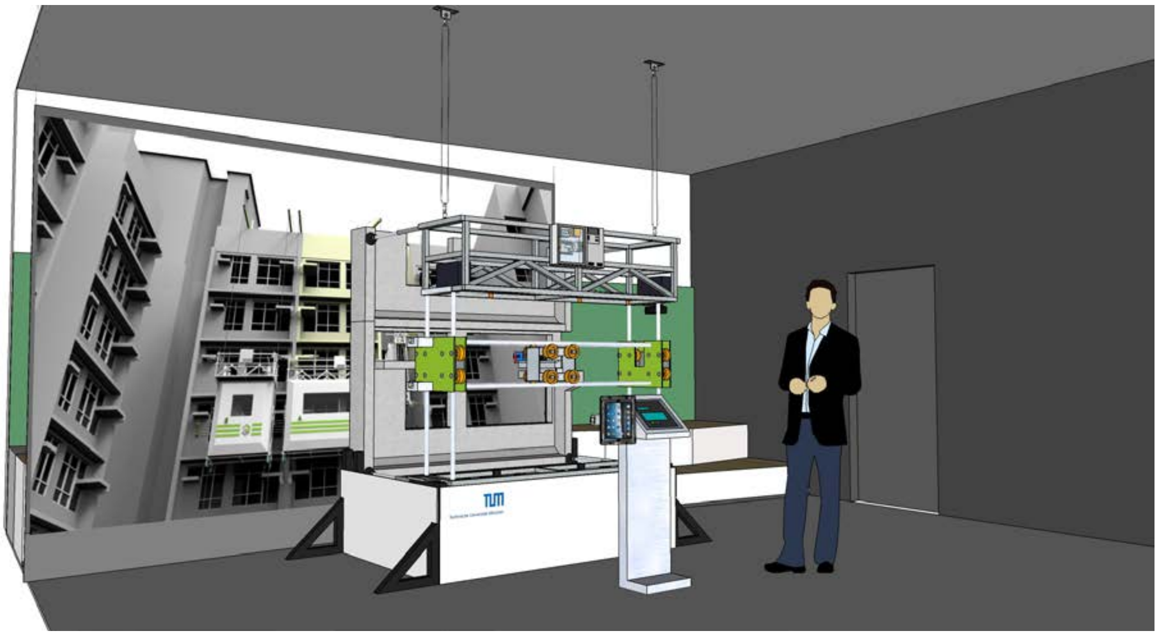


Figure 5-40: Final visualization of the demonstrative mock-up

5.7 Conclusions

Key insights and outcomes with regard to the development of prototype (mock-up) of the façade-processing robot for demonstration and exhibition at CITAC

1. The detailed costs of manufacturing the fully functional prototype and the scale mock-up are explained.
2. The reason why the scale mock-up instead of full-size prototype is manufactured is explained.
3. The overall information of the scale mock-up (e.g. design, dimensions, functions, etc.) is introduced.
4. The details of all the mock-up components is introduced.
5. The demonstration and exhibition plan of the mock-up at CITAC is considered.

6 Process information modeling (PIM) concept for efficient on-site robot deployment

Public building construction, which consists of many sub-tasks and numerous systematized working processes such as planning, mobilization, scheduling, procurement and controlling, is complicated. If the project team is incapable of managing these processes seamlessly, it may result in severe project delay and cost overrun. This issue becomes even more apparent if utilizing construction robotics, since precise process and scheduling information as well as feedback is required to ensure that the completion of each task is correct and on time. However, lack of software infrastructure and compatibility means that there is no existing software would be able to accommodate and synchronize robot operation with the existing Building Information Models (BIM) or other management programs. Lack of such software, inadequate hardware integration can lead to entire system failure. This is also one of the reason caused the Japanese approaches of the single-task-robots to fail in the 1980s due to excessive setting up time. Potentially, PIM will open up a new business market in the software application field. By implementing construction robotic and automation technologies, Hong Kong will be in the forefront of such software integration activities, which will be further developed in the follow-up project and to influence the design, operation, lifecycle management and business model of the future construction robotic systems.

In this chapter the process-oriented modeling approach, PIM, which provides a collaborative way of planning, designing, producing, assembling and entire project life cycle management strategy is introduced. The main objective of PIM is to integrate with the conventional BIM and supplement them with a process oriented database platform, allowing for smooth data transfer, as well as promoting seamless and constant data sharing among all stakeholders. Digital documentation, simulation and real-time data are produced progressively to support the decision-making process. The effectiveness of the PIM is demonstrated on façade painting task by a painting robot for an on-going consultancy project commissioned by the construction industry council (CIC) in Hong Kong. The impacts of PIM on supporting the potential future applications of construction robotics and instigating the next construction information evolution are discussed.

6.1 Background

For many years, researchers have agreed that efficient integration and coordination of design, construction, and management data can potentially benefit the overall performance of the construction industry **(Higgin & Jessop, 2003)**. Recently, other industries are flooded with data; the construction industry is not an exception to this unprecedented trend. In each step of a construction project, the project team will be dealing with enormous data, which amongst various professions and the decisions were made could impose serious implications on the construction project. Currently, Building Information Modeling (BIM) technologies are being considered able to deal with multi-dimensional CAD information systematically, improve data integration among cross-disciplinary collaboration across the industry and between the key stakeholders.

Even though BIM can cover the construction project span from early stages to the completion of the project, the implementation of BIM technologies is often fragmented in most of the construction projects. This is partly because, in practice, BIM does not effectively categorize or integrate the most relevant data and distribute the information to the most desired stakeholder. A piece of information cannot function alone without specific protocols and relationships behind it **(Dossick & Neff, 2009)**. The BIM technologies should be able to provide a platform, where the data collected from each phase of the project can be integrated and allow interoperation between various applications **(Eastman, Teicholy, Sacks, & Liston, 2013)**. Therefore, the concept of the next generation of BIM is not merely just gathering information or use of several of technical tools, but also managing information across diverse collaboration and interrelationship of the key stakeholders. Additionally, it is essential to deliver the right information to the right place for the right people at the right time **(Jernigan, 2007)**. Process Information Modeling (PIM) has the potential to be developed as the next generation BIM, which will enhance information integration, yet focus on the process of each construction tasks and the relationship between each attribute. In this case, the attributes can be people, products, processes or technologies. By doing so, it helps the project team to identify challenges of execution from both technological and social approach, and provides feasible solutions proactively **(Trist & Bamforth, 1951)**. The detailed description about PIM is demonstrated in the later section.

This chapter proposes a scenario in conjunction with the ongoing consultancy project commissioned by the Construction Industry Council (CIC) in Hong Kong. It hypothesizes the PIM concept applied imperatively to the utilization of a façade painting robot. In general, the Hong Kong Public Housing Construction (PHC) sector faces three major challenges: (1) to satisfy the increasing demand; (2) to achieve affordable price and (3) to address demographic changes. Accordingly, the CIC commissioned the Chair of Building Realization and Robotics (br2) at Technical University of Munich (TUM) to research and develop construction robots and automation strategies that are tailor-made for the PHC in Hong Kong. The proposed external painting robot provides an opportunity to develop and validate the PIM concept. The implementation of construction robotics will trigger a series of changes in the construction sequence and potentially revolutionize the construction industry as a whole. It is the commitment to meet the challenges of the collaboration of the academia and key stakeholders to launch a significant attempt for developing a tailor-made process-oriented approach based on the current BIM technologies.

Although research was done based on the topics of BIM, limited research topics were conducted related to the topic of how to implement BIM technologies when adopting robotic and automation technologies in the construction project. There are raised few remaining questions, such as, whether the existing BIM technologies are still adequate to handle the tasks when implementing robotic automated operational methods and working processes, which dramatically differ from the conventional way, If not, is the proposed PIM concept able to tackle the challenges and how? This research forms the backbone for developing PIM applications in the future. However, due to the lack of available resources and complexity of the construction process, the PIM applications can only be conceptualized.

Consequently, the authors evaluate the current BIM and big data technologies through an extensive literature study to explore the potential constraints within each key project phase and exam how to transfer those constraints into opportunities for the construction sector and beyond. The proposed PIM concept offers a practical approach, which can be used as a guideline to integrate and distribute information and enhance decision-making procedures during the design, precedent and tendering, logistics, construction and facility management phases. As a result, the proposed PIM approach can yield a huge change in how the construction industry handles such large volumes of heterogeneous data, as well as enhance information acquisition and integration, which provides real-time data sharing among all key stakeholders. In addition, it lays a foundation for developing a practical PIM application in the future.

6.2 Building Information Modeling (BIM) and Process Information Modeling (PIM)

6.2.1 BIM

Recently, BIM is one of the most promising developments in the Architecture, Engineering and Construction (AEC) industries. BIM became more influential within construction projects, which is commonly used in the design, visualization, planning, facilities management and cost estimating purposes. Using modern modeling tools, such as Revit Architecture, ArchiCAD or Tekla Structures, the content produced by architects, designers and engineers have evolved from traditional 2D-drawings, sketches and written specifications to parametric, object-oriented 3D-models embedded with information to describe any building or facility in detail **(Pan, Langosch, & Bock, 2017)**. With BIM technology, an accurate virtual model of a building is digitally constructed **(Azhar, Nadeem, Mok, & Leung, 2008)**. When integrated efficiently, the computer-generated model contains precise geometry and relevant data needed to support the construction, fabrication and procurement activities involved in the project. Although BIM applications claim to possess seamless integration of data from each project phase, in practice it is less evident how accurate and rapid the data was passed on and how the data was utilized. This may be a result of the availability, compatibility and interoperability between raw data and the applications. These aspects determine if the data can be transferred, integrated and responded to in real-time. On the other hand, BIM application is a knowledge-based and object-oriented approach that aims to digitally and visually represent the real world situations. In other words, it can be considered as the identical twin of the real world. This might sound unrivalled, however, when implementing construction robots or carry out a complex construction project, only understanding the real world condition is not enough. Expertise based, interactive, proactive and responsive extension of BIM is required (Harty, Throssell, Jeffery, & Stagg, 2010).

6.2.2 PIM

The widespread use of digital technologies will lead to huge amounts of data being generated throughout the construction process. Some of the data is well understood by the stakeholders, for instance, Computer-aided design (CAD) data, Excel data, 3D virtualizations. On the other hand, some of the other data may be less familiar to the stakeholders, and it greatly depends on their experience, background and professional field. The main objective of PIM is to make sure that everyone understands the data correctly; to predict what is going to happen in the future based on the existing information variables. Specific actions need to be taken for analyzing the risks and challenges that might occur and then recommending the options to the decision-maker in real time **(Pistorius, 2017)**.

PIM application is a process-oriented, case-focused approach that provides detailed information about a specific task. It then breaks down into smaller, manageable data and is distributed to the right stakeholder at the right time. The recipient can plan; the recipient can react to the distributed data by following a guideline generated by PIM. The main feature of PIM is to optimize the entire construction process - rather than optimizing some parts and neglecting the others - by offering rapid, consistent data management and providing interactive, proactive, responsive data integration. In addition, it will be equipped with cooperative and interoperable program applications that offer information, which can be understood by the stakeholders, rapidly accessible, predictive analytics as well as provides feasible guidance when issues occur **(Pan, Langosch, & Bock, 2017)**.

In principle, PIM consists of five fundamental stages, which include project break down, data management, PIM Big Data (PBD) architecture construction, implementation, and PBD distribution. During the Project break down, each project stage is formulated as an individual data cluster, which can be deployed, assessed, processed and transferred independently. For example, the initial data clusters shall include; design data, production data, procurement and tendering data, logistics data, rapid construction data and life cycle management data. As a result, the data clusters are loosely coupled, and they provided the database that can be categorized, classified and shared with the relevant party. The human data, physical data, project management data, facility data and cyber data will be analyzed. The main goal of this stage is to differentiate and integrate the data based on the relevance of the information evaluated by the key stakeholders. This action can potentially enhance interdepartmental, cross-functional and cross-disciplinary data interaction; therefore, it adds value throughout the project.

During the next stage, PBD is further categorized into four main databases, which are the physical database, the BIM database, the Internet of Building Things (IoBT) database and the maintenance management database. The physical database contains the information that is gathered through paper-based hardcopy documents, as well as the information not yet transferred into digital data. The BIM database covers the range of information from basic data to highly sophisticated implementations, which include 3D, 4D, 5D and 6D BIM applications. The IoBT database comprises a range of smart data collected throughout the construction phases, which include geolocation tracking, monitoring of equipment, inventory, procurement management, quality inspection, real-time measuring and control, and remote operation. The maintenance management database covers the information accumulated over repairing, alteration, conversion, upgrading, scheduling and budgeting aspect of life cycle management activities **(Pistorius, 2017)**.

The aforementioned data is collected and stored in the PIM data Processing Unit (PPU). PPU is not only for data acquisition, rather most importantly for a range of interoperable applications that actively process data in real time and analysis huge amounts of data created from a variety of sources. The main strategy of PPU is to process, integrate, transfer, share and store the real-time data. In addition, it enhances collaboration and supports the decision-making activities by distributing the most relevant information to the right key stakeholders at the right time. At the time of this writing, PIM is only developed as a conceptual model that demonstrates the overall concept, yet capable of offering basic instructions and data analysis that based on the scenario created by the Hong Kong CIC project (see *Figure 6-1*).

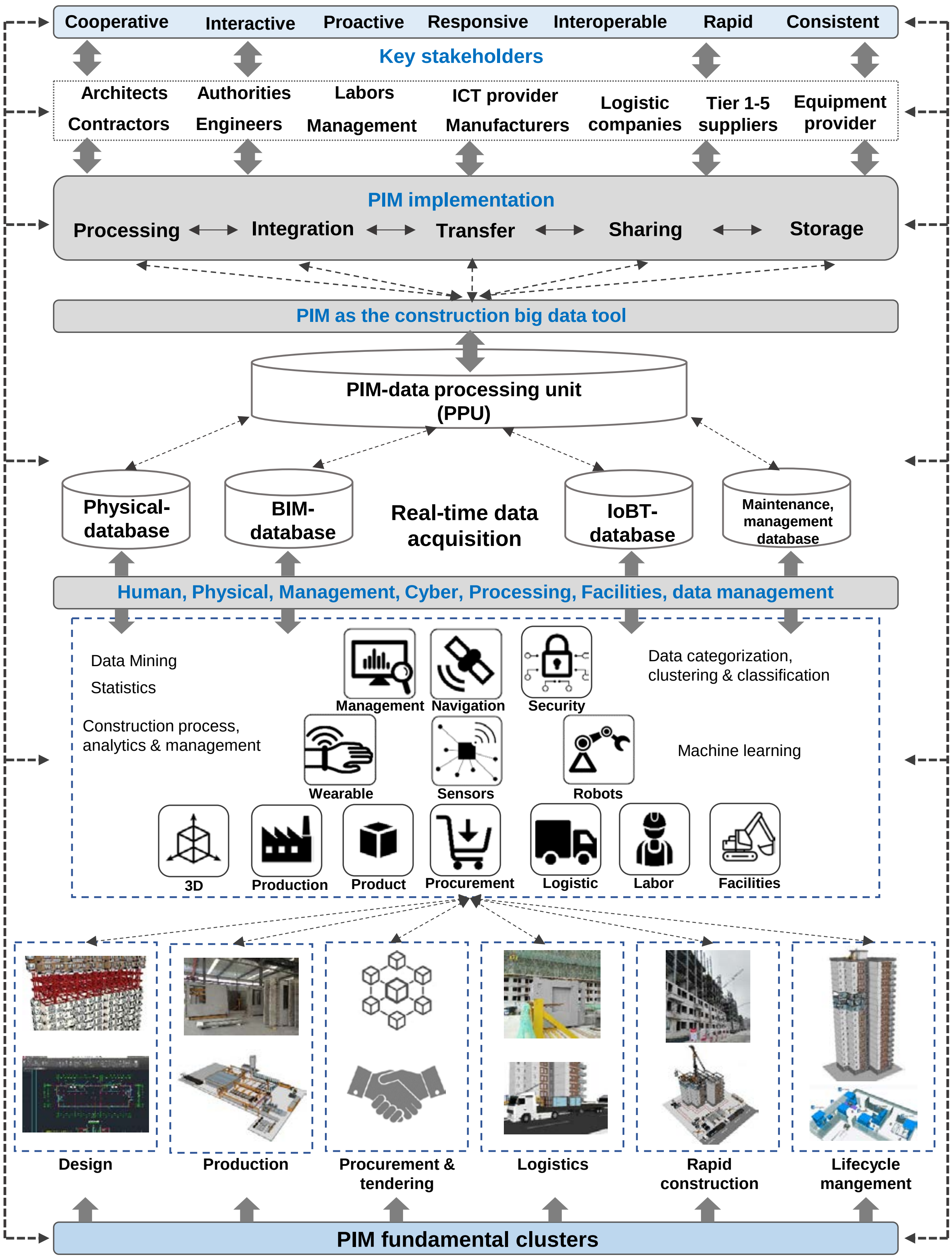


Figure 6-1: Process Information Modeling concept (Pan & Ilhan, 2018)

6.3 Literature review

The construction industry is dealing with significantly increasing data from various disciplines throughout the construction process. As mentioned earlier, the PIM proposal can be seen as Big Data application. Utilization of the applications can yield momentous benefits for an organization or individuals undertaking a variety of complex construction projects. In this section, the literature review and theoretical background are briefly introduced.

6.3.1 Big data

In general, Big Data consists of two main activities, including Big Data Engineering (BDE) and Big Data Analytics (BDA). First, Big Data accumulates huge amounts of data and then processes them with tools such as Apache Hadoop (AH) and Apache Spark (AS). Secondly, Big Data storage is another crucial task, which manages the data distribution or emergence.
Apache Hadoop: The AH is an open-source implementation of MapReduce (MR) **(Dean & Ghemawat, 2008)**. It is designed to manage very large nodes of the database on computer clusters that are constructed from commodity servers. Nowadays, many web-based brands use Apache Hadoop platform, such as Yahoo! and Facebook. Apache Spark: The AS is one of the many open-source cluster-computing platforms for processing large-scale data. It has gained increasing popularity recently due to the processing speed and user-friendly feature. It is fault-tolerant and optimized by Application-Programming-Interface (APIs) in interpreted high-level programming languages, such as Python, Java, R and Scala **(Zaharia, et al., 2016)**. With the increasing amount of heterogeneous, autonomous parallel-distributed sources and data, BDA has become crucial for many business disciplines. In general, BDA provides a new paradigm on how to handle, storage, manage and access to those huge datasets **(Miller, Bowman, Harish, & Quinn, 2016)**.
Starfish: Commonly, starfish is a self-tuning system used by data scientists, business analysists and IT operators to visualize, optimize, and strategize the AH application. It builds on the AH application and adapting user’s needs to achieve better performance automatically **(Herodotou, et al., 2011)**.

6.3.2 SODATO

SODATO stands for Social Data Analytics Tool that is developed to provide a generic method to gather, store, process, analyze and summarize big social data, which accumulates through the organization’s social media platforms. It provides a strategic tool that actively interacts with the big social data **(Hussain & Vatrapu, 2014)**.

6.3.3 Programming language

During the development of the PIM concept, it was evident that there are various examples in computer software design, which have conceptual principles similar to those in PIM. A brief analysis is conducted to offer a reinterpretation of the PIM concept by using software programing concepts **(Pan, Langosch, & Bock, 2017)**. Service-oriented architecture (SOA) can be described as a loosely coupled program architecture designed specifically to meet the needs of an organization **(Arsanjani, 2004)**. By using communication protocols, which provide services to another component and make connections between different software components over a network **(Erl, 2004)**, the definition of a service can be viewed as a logical representation of a repeatable task. SOA is independent, self-contained, yet when combined, it forms the functionality of a large software application. The unit architecture in PIM also shares similarities with the service architecture in SOA. It is beneficial when linking an agent influenced by the unit data or service. Furthermore, the changes would influence the individual agent's capabilities or responsibilities **(Pan, Langosch, & Bock, 2017)**. The Microservice architecture is a programming concept inspired by SOA. Instead of traditional monolith software application, Microservices provides groups of independent program components that are operated and deployed separately, however still based on precise protocols and dedicated memories. The Microservice architecture gained popularity in the recent years; it has potential to contribute to the development of PIM concept. However, there is limited research that highlights the topic **(Nwana, 1996)**. Therefore, further validation through application use-case is necessary. Service discovery, or service discovery protocols (SDP), is an emerging field in the area of ubiquitous computing **(Richard & Spencer, 2001)**. They provide a mechanism, which allows automatic detection of service offered by any node in the network. In other words, service discovery is the action of finding a service provider for a requested service **(Czerwinski, Zhao, Hodes, Joseph, & Katz, 1999)**. Service discovery can potentially operate as a search engine for the PIM architecture.

6.3.4 System integration

Due to the complexity of the construction projects, the multidisciplinary stakeholders and implementation of heterogeneous data using different software and hardware are hard to manage. Data integration becomes very critical, which enables smooth operation and effective collaboration **(Shen, et al., 2010)**. A number of challenges regarding to data integration within the construction, were identified by FIATECH **(FIATECH, n.d.)**, which can be summarized as below:

- There is a lack of transferability and interoperability between data, systems, programs and methodologies,
- The comprehensive universal management tool for different phases of the construction project is still not available,
- Life cycle management issues are often not emphasized. Operation, maintenance, dismantle and recycling are taken in consideration less,
- There is no common tool to manage health safety measures, and predictions of operation hazard are not available.

As a future construction IT system, PIM application will ensure construction information is available on demand the transfer to the desired stakeholders at the right time. All project partners, construction tools, equipment and machinery will be interconnected through integrated management systems. This will enhance planning, enable rapid response and optimize overall running of the project **(Rezgui & Zarli, 2006)**.

6.4 PIM concept development for external wall painting task

In this chapter, the project team uses the 14-story building as a case study to investigate how to implement PIM application to carry out the external façade painting task by using a painting robot, which is developed during the CIC project. First, the detailed breakdown of the working sequences, involved stakeholders, and data for the exterior wall painting task are analyzed. Whereas *Figure 6-2* demonstrates the workflow for the façade painting task carried out by a painting robot, *Table 6-1* presents the corresponding data for each task description. The main purpose of the proposed approach is to provide an automated process through accurate information flow from design phase to construction phase. Extension of the data stored in the BIM software is achieved by developing a property set. Pset_CIC_Painting is generated for schema IfcArchitectureDomain in the domain layer of the general Industry Foundation Classes (IFC) architecture. IFC is a cross-platform, open file format to describe data of the building and construction sector, which is not controlled by an individual or a group of individuals. It has the properties of PaintingRobot, PaintingMaterial and MaxHeight. Data types for the criteria are set as IfcBoolean, IfcPropertyEnumeratedValue and IfcReal, respectively. PaintingRobot finds out whether the façade painting is performed by a robot or not, wherein MaxHeight refers to the maximum height of the external wall and PaintingMaterial includes the paint information. The CIC template file including the extended properties and building materials/composites for façade painting is created. The user should assign each property using the IFC Manger menu. Pset_CIC_Painting is applicable to the project entity. Then, BIM file is exported as IFC format and transferred to an Excel file via IFC File Analyzer (IFA) **(NIST, n.d.)**. In case PaintingRobot returns TRUE, the relevant data for the corresponding process can be extracted for the painting with automatic application.

Table 6-1: Robot-oriented painting task and related data (Pan & Ilhan, 2018)

Task description	Data bank
Installing the suspended working platform	Product, logistic, planning, bidding, labor, equipment, health & safety, repair & maintenance data
Delivering the painting robot and other accessories	Robot, logistic, planning, bidding, navigation, distribution data
Setting up & calibrating the painting robot	Robot, planning, equipment, repair & maintenance
Cleaning and preparing the external wall, skim coating of the wall	Robot, bidding, planning, equipment, repair & maintenance, labor
Applying the first coat of paint	Robot, paint supply, planning, equipment, repair & maintenance, labor
Conducting quality inspection	Robot, planning, equipment, authority
Applying the second coat of paint	Robot, paint supply, planning, equipment, repair & maintenance, labor
Conducting quality inspection	Robot, planning, equipment, authority
Applying the final coat of paint	Robot, paint supply, planning, equipment, repair & maintenance, labor
Conducting quality inspection	Robot, planning, equipment, authority
Finishing the areas where need to be painted again	Robot, paint, planning, equipment, repair & maintenance, labor
Dismantling the painting robot, hoisting device	Robot, planning, equipment, repair & maintenance
Dismantling the suspended working platform	Product, logistic, planning, labor, equipment, health & safety, repair & maintenance data

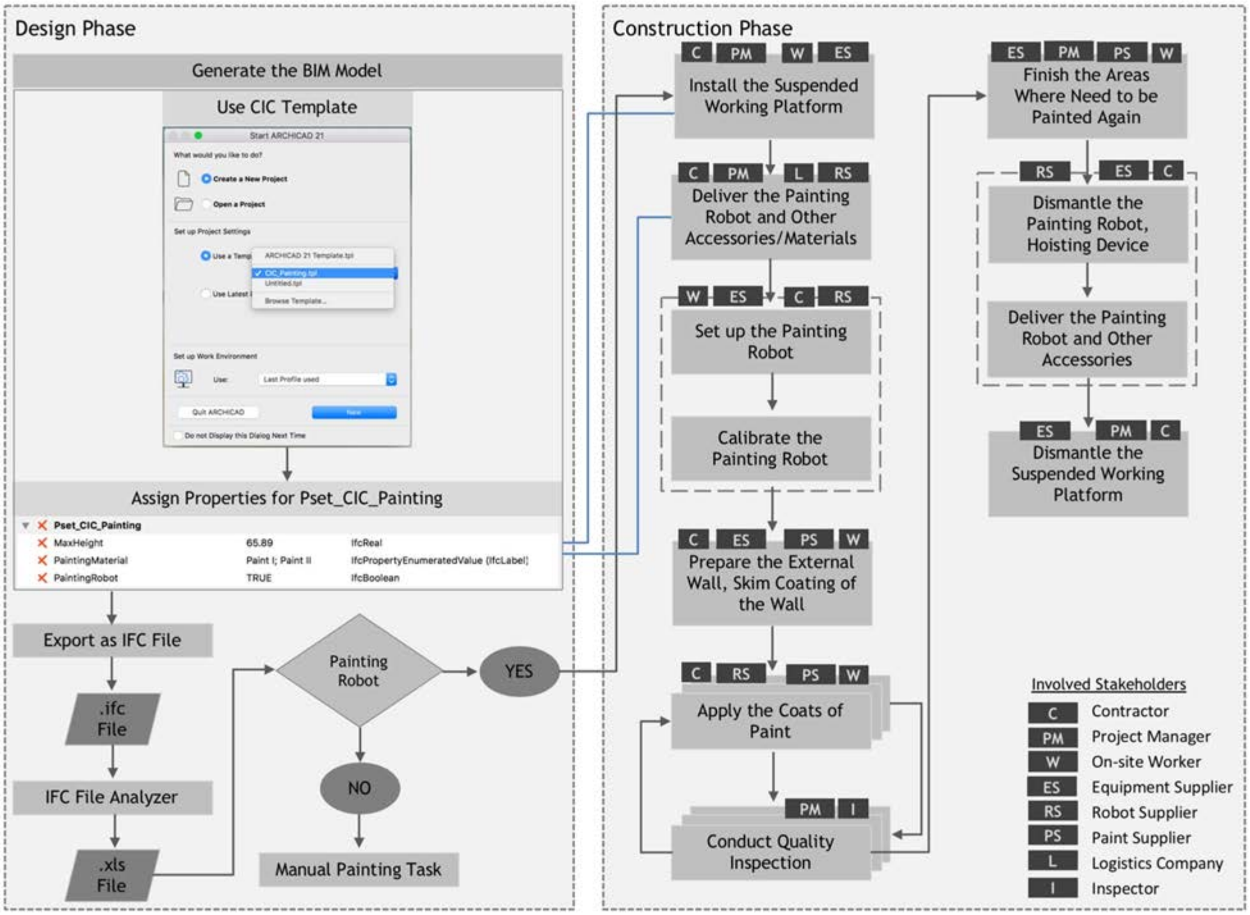


Figure 6-2: PIM-based external wall painting task flowchart (Pan & Ilhan, 2018)

6.5 Key outcomes and integration with the façade-processing robot

This chapter provides an overview of the PIM concept and introduces a use case demonstrating how PIM applications would be operated while using the construction robotics on-site. The conventional BIM applications are designed to collect and distribute basic information about the construction project. However, they are not adequate in dealing with the situation the construction robots are implemented. Since they have a limited function to understand the operational data generated by sensors and robots, there is a need of a more comprehensive approach. The concept of PIM enhances all aspects of the construction operations by not only collecting and distributing the data, but also by proceeding and analyzing them in order to optimize the decision-making during each task. The proposed approach provides systematic information flow and management for the construction phase of the project life cycle via incorporating the BIM data. This design and construction data-integrated solution enables improved construction process management. In the current situation, BIM facilitates the design stage of a construction project and provides accurate project information. Moreover, the continuation of the construction processes is separately handled based on the design data. Nevertheless, since most of the project delays and consequently cost overruns arise from the construction phase, more integrated and automated methodologies should be adopted. For instance, if the correct material/equipment information is gathered and transferred to the corresponding stakeholder as rapidly as possible, the necessary actions can be made prior to the actual construction. This provides the opportunity to prevent any possible delays (e.g. in the façade painting case, checking the supplier of the paint automatically and in case of unavailability of that supplier, searching the possible ones via warning the related parties). Moreover, the chapter functions as an eye-opener to the construction industry through a demonstration on how to carry out BDE and BDA activities that associate with the vast amounts of heterogeneous data. As mentioned earlier, at the time of this writing, it is limited to the conceptualization of PIM. PIM is only developed as a conceptual idea that establishes the overall concept, yet will not bear on its ability of offering basic documentation tasks, and will provide instructions and data analysis by using existing Microsoft Excel tool. In addition, a comprehensive research project is needed to develop the concept further. It is important to use a real case study to develop the hardware and software environment, which is required by PIM developers. Due to the given time and resources, the potential of the PIM application as a future Big Data application for the construction industry, and privacy or data protection issues were not discussed in detail.

This PIM system can be applied in various robotic construction tasks including the proposed façade-processing robot. First, an Integrated Software Platform (ISP) with a user-friendly User Interface (UI) needs to be developed. The ISP consists of three major sub-systems, which are the PIM simulation & optimization, the real-world execution, and the real-time monitoring. In the PIM simulation & optimization process, the task is simulated in a robot simulation software in which the model of the robot and the target building BIM model can be imported, in order to estimate the duration and optimize the time schedule of this task. After the optimized schedule of task execution is generated, the schedule and the code of instruction will be sent to the façade robot on the job site for real-world task execution. Finally, by adopting 3D mapping and navigation technology, the real-time monitoring system will be responsible for inspecting and assuring the quality of the task. *Figure 6-3* indicates the proposed strategy to integrate PIM concept in this consulting project.

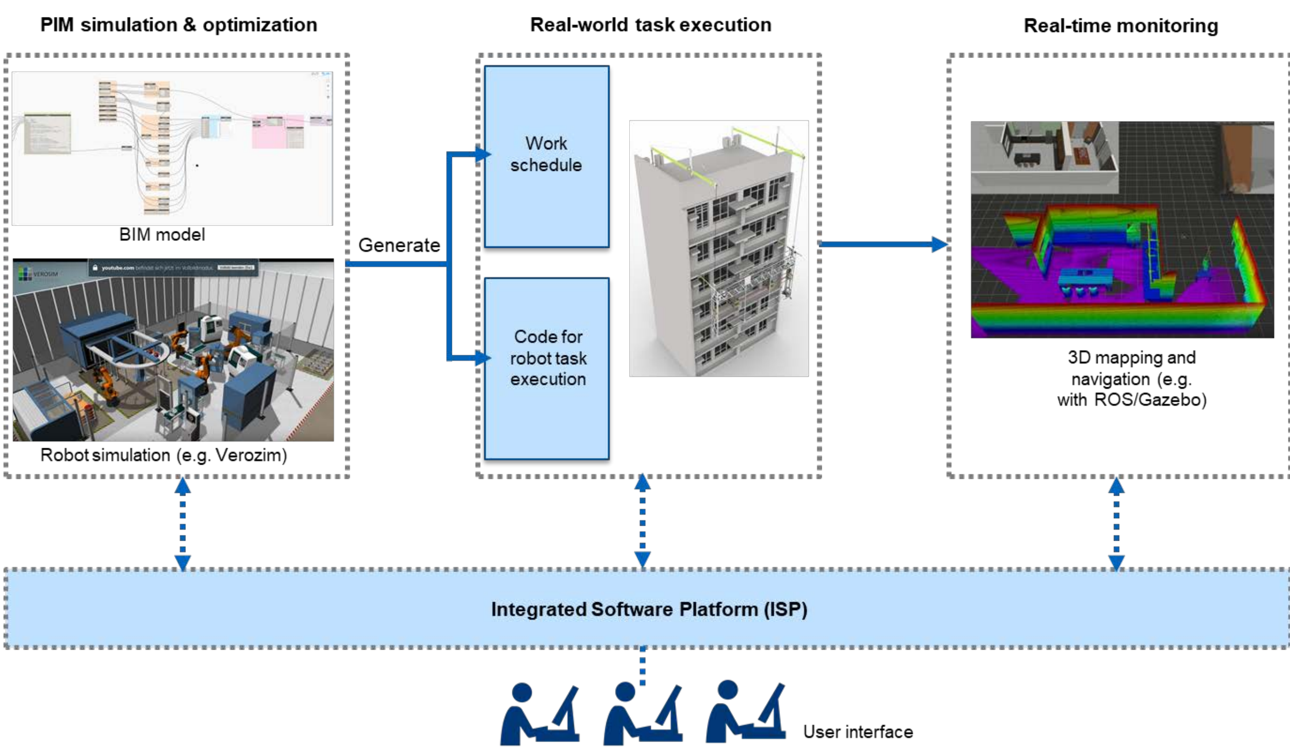


Figure 6-3: Synergies with and extension of BIM support fast and efficient set up and operation of the robot

6.6 Conclusions

Key insights and outcomes with regard to process information modeling (PIM) concept for efficient on-site robot deployment:

1. The background of Process Information Modeling (PIM) is explained.
2. The comparison of Building Information Modeling (BIM) and Process Information Modeling (PIM) is conducted.
3. The literature review of the key technologies in PIM concept is conducted.
4. The PIM concept development for external wall painting task is introduced.
5. Key outcomes and the future research roadmap for PIM concept are indicated.

7 Business strategy and market implementation recommendations

Business strategies/models lead to design inputs and design requirements that need to be integrated into the robot design from early conceptual stages onwards. For example, the question that who operates a robot is crucial with regard to things such as the complexity of the robot or the performance of the control interfaces, and for/by whom it is actually designed. Thus, the points discussed in this chapter were used as design inputs also for the exemplary detaining of the façade processing robot. For the follow-up project, finding the appropriate business strategies/models will be even more important for developing a marketable version.

In simple terms, a business model helps organizations to realize the economic value of their product, services, business and/or technology. The model clearly highlights where the business is in the value chain and what the consumer will get out of it. A clear business strategy is crucial to the success of any business and is the foundation of optimizing innovative technology - a must in today's competitive global marketplace. Without a business model, new technology can have limited value. A successful business strategy can maximize the commercial return from this high-cost investment, as well as drive innovation **(Osterwalder & Pigneur, 2010)**. In this section, the appropriate business strategy and its implementation recommendations for the proposed robot system will be discussed.

7.1 Current facts of Hong Kong construction market and industry

The Hong Kong construction market is at its most active, yet stable stage. It is expected that the ongoing and upcoming large-scale public infrastructure projects will help keep the number of construction projects in Hong Kong maintained at the currently high level. These key public projects cover the bridge, highway, commercial area development and public housing, one of which is the long-term housing supply plan for 480,000 units over the next 10 years **(Census and Statistics Department, 2016)**. According to Frost & Sullivan, a global consultancy, the scale of the construction engineering market in Hong Kong is expected to reach 173.2 billion HK dollars in 2020. However, it cannot be ignored that some constraints and trends appear to influence future project implementation, in spite of a seemingly prosperous market **(Financial Times, 2015)**.

(1) Aging labor force and labor shortage.

On the one hand, experienced skilled workers are quitting or retiring. According to statistics, as of the end of 2014, about 44.4% of construction workers with more than 10 years of experience in Hong Kong were over 50 years old. Meanwhile, more and more attractive construction projects in mainland China and Macau with high pay attract further industry professionals and experts leave Hong Kong, On the other hand, the number of young people who are willing to join construction industry is declining due to over-emphasis on social status and reluctance to engage in hard blue-collar construction work. Therefore, the labor force in the Hong Kong construction industry became increasingly scarce and even caused some infrastructure project postponement. Currently about 125,000 construction jobs cannot be recruited in Hong Kong, especially the dangerous outdoor ones. At the same time, the local people do not accept the integration of immigrants and the problem grows more complicated **(Financial Times, 2015)**.

(2) High cost.

Lack of labor supply leads to continuous rise of construction costs as the cost of labor rises. Hong Kong remains to be the city with the highest construction costs in Asia and becomes the second highest one around the globe after New York, according to the analysis of Arcadis, an architectural asset design and consultancy company, on 44 major cities worldwide in its International Construction Cost Index **(Financial Times, 2015).**

(3) Increasingly high housing price.

The above factors inevitably push up the housing price in Hong Kong. Hong Kong is now the most expensive real estate market in the world. The private property price continues to hit record highs, although the government repeatedly launched the "hot trick" policies in order to cool down the market price. More and more people queue for public housing with longer waiting time.

The Hong Kong construction market is such an open one that players over the world can join to compete relatively equally. That means, whoever meets the requirements of government and finds a better solution or technology against those constraints will likely win the future market. Adding the expected market capacity in Hong Kong allows the possibility of investment in new technology application, therefore, no matter the government or the construction industry in Hong Kong, at all their interests, shall focus on investing in real effective solutions and measures that can help increase industry productivity and sustainability.

7.2 Feature comparison between façade robot system and human labor

From the above facts and analysis, the labor issue prevails to be the most important for the Hong Kong construction industry development. Thus, robotics can be considered as a long-term solution to mitigate and offset labor-related impact. In this report, we will focus on the façade robot system, which can replace labor jobs in the original dangerous and harmful labor-intensive, yet labor-shortage fields, such as building's fine plastering, grinding, painting, cleaning, inspection and marking, façade installation and replacement, and piping installation. Due to the specific quality requirements of Hong Kong, these jobs have to be done onsite. *Table 7-1* demonstrates the comparison between human labor and the façade robot system.

Table 7-1: Comparison between human labor and façade robot system

Features	Human Labor	Façade Robot System
Safety	• Dangerous. Heavily rely on labor's operational behavior and quality of lift standing equipment; • Harmful. Some dust operations, e.g. painting and fine plastering etc., even cause professional diseases or other long-term health problems; • More insurance are needed.	• Safer, reduced hidden danger; • No concerns toward human health • Tremendously reduce insurance cost and long-term social healthcare burden.
Quality and Reliability	Can be controlled, but hard to keep the same level and stability as different labor varies or same one differs due to personal conditions, e.g. health, mood, weather interference etc.	• More reliable in terms of quality stability • Can reach standardized high level with continuously improved design

Productivity	• One person operates one equipment each time • Individual upper productivity limit can hardly be exceeded	• One person can operate several robot systems at the same time • Productivity limits are likely constantly increased through improved design • Reduced number of labor required
Supply Sustainability	Keep declined due to aging and shortage	• No shortage concern • More sustainable
Attendance	Can be influenced by disease, vacation, or other personal issues	• No external interference • Need regular maintenance
Training	Need for each specific job	No need for each job but only operating system, reducing training cost and period
Working Hours	• Has limitation • Low flexibility	• No limitation • More flexible
Cost	• Short-term advantage • Continuously increasing in long-term	• Relatively higher at the beginning and in short-term • Constantly reduce in long run if considering 25 years of life design • System price can be tremendously reduced with scaled production and application
Plan and Preparation	• Relatively inflexible schedule plan • Need longer preparation time	• More flexible and adjustable plan • Shorter preparation time
Multifunction	• Difficult • Need more training and longer experience accumulation period	Relatively easier to realize by a changeable versatile plug-and-play end-effector system design

7.3 Benefits of the robot system for the related stakeholders

By implementing the façade robot system, the following stakeholders will enjoy major benefits as listed below.

(1) On the government and CIC level:

- Industry safety is substantially improved;
- Related working quality can reach a fairly stable and good level and become more controllable;
- It helps defeat the constraint in labor shortage to better control the house price rise in long run caused by higher and higher labor cost. Besides, it reduces the risk of project delay which is quite crucial for public housing projects;
- Productivity in related fields can be maintained or even improved;
- Improvements in the working environment coupled with increase in technological content of job will attract more young people into the industry;
- It is likely to lower public insurance expenditures and reduce social burden in healthcare in the future.

(2) On construction enterprise level:

- Improve the site safety for the workers;
- Higher working efficiency for the repeatable works;
- Furthermore, by using the new technology, it may help win the future market.

(3) On robot leasing and service provider level:

- The trend will change the model of revenue and profit generation. These two types of users are likely to obtain new business sales through applying the robot system as if they find the proper business model.

(4) On manufacturer level:

- Any new potential market will attract participation of manufacturers. Then the first mover will gain some advantages.

7.4 Business strategy for the façade robot system at the current stage

Thanks to the construction market of the long-term public housing supply in Hong Kong, the opportunity and proper timing to invest in and apply new technologies is available. In order to promote the technology of the facade robot system and the application, a synergy from all sides is necessary.

(1) <u>The proposed robot system shall expands its volume of capability as long-term economic consideration</u>

The designer of the robot system needs to provide the solution not only practically and efficiently, but also economically from an application point of view. Currently, according to the feedback from the site visit, the façade painting task in Hong Kong's public housing construction is estimated to be approximately only 1-2% of the overall construction cost. Therefore, as demonstrated in Figure 4-20, in order to maximize the potential building budgets we can tap into with the façade-processing robot, it is important to expand the volume of the tasks, which the proposed robot system can undertake (i.e., from only painting to other façade tasks). The final goal is to cover 10-15% of the construction cost of a building with our robot through the modular task expansion through end-effectors (thus, all faced exterior processing tasks). Moreover, it is also important to enlarge the building types where the robot system can be applied (i.e., from public housing to other building types).

- Make a multifunctional design in the most economical way. For instance, the robot system can do different types of jobs just by one changeable part. These jobs include building's fine plastering, grinding, painting, cleaning, inspection and marking, façade installation and replacement, and piping installation etc. That is why the proposal provides a versatile plug-and-play-end-effector system design. It helps reduce equipment investment costs.
- Enlarge application scenarios. The system is not limited to public housing application. It can also be applied to other constructions, such as an office building, a hotel, public & commercial building, factory, and shipyard with optional changeable plug-and-play end-effectors.

(2) <u>Government must play a key role in providing incentive policies to initiate application</u>

At the beginning stage, the biggest obstacle comes from the users' cost concern. Thus, the incentive policies from the Hong Kong government are quite critical to push the application. The government may consider requiring the successful bidders to use new robot system by providing low-interest or interest-free loans during the first years. Another possible method is to support a new form of service center, which can not only lease the robot system, but also provide related façade services with the PPP model. Finally, it will all lead to the upgrade of the Hong Kong construction industry and make it more technology-driven for future preparation.

(3) <u>CIC shall be an important general coordinator platform</u>

Besides playing a key coordinator in the complete project of the robot system application in Hong Kong, CIC can build an intelligent platform as well to provide consultancy, training, and accreditation activities. It can organize and collect practical feedback from the users for better technology improvement at an early stage when helping the government make proper policies.

(4) A new form of service-oriented leasing center can be considered
Different from construction contractor, a service-oriented leasing center is more flexible and possible to generate new business domains and profits. On the one hand, it can lease the robot system for return of investment. On the other hand, it can be the service provider itself to different construction projects or after-construction services. These services will bring new profit growth and a shortened investment return period. This model will provide the center comparably lower construction costs with respect to construction enterprises, who the robot system.

(5) Cooperating with existing manufacturing fields will be a possible solution
As Hong Kong is such a service-driven city, it is difficult to locally support manufacturing-based companies. Therefore, cooperating with nearby existing ones, (e.g. some in mainland China), is a more realistic solution in terms of cost for the scale production of the robot system.

(6) Accreditation scheme for construction robotics
TUM will closely work together with CIC to develop the training and standardization program for operating and maintaining the robot system. Certification of operating and maintaining the robot system for the trained workers will be issued by CIC. In order to ensure the training quality, the contractor/real-estate company needs to provide the training ground for the workers to practice in real-world conditions. Details regarding the accreditation scheme can be seen in *Section 8.3*.

7.5 Assumption of the cost reduction and payback time using painting as an example

The project team assumes that the proposed robot system will save up to 10% of the existing labor and material cost, which is a relatively feasible goal. Then based on the data collected from site case study the approximate cost of the painting task is shown in *Table 7-2*:

Table 7-2: Cost estimation of the current painting task in the case study building

Cost position	Total cost (rough estimation)
Renting/ using Gondolas	HK$ 400,000
Grinding, preparation	HK$ 700,000
Administrative overheads	HK$ 200,000
Labor & material	HK$ 1,200,000
Total	HK$ 2,500,000
Profit	Approx. 5% = 125,000

According to the estimation, the potential saving per building would be HK$ 120,000, and the profit margin would increase by 200% (i.e., HK$ 245,000). As the initial estimation, the cost of the first functional prototype will cost in the range of HK$ 1,925,870. However, the prototype will always cost more than the mass-produced final product. The project assumes that the aimed target cost for the final system is approximately HK$ 963,140. Then, the payback period would be less than 2 years, which is equivalent to the duration of the completion time for four buildings. This also depends on the work value of the contractor. In principle, a faster payback time will be achieved when the system is more frequently implemented.

7.6 Education and training

Labor shortage is one of the most crucial issues facing the construction industry of Hong Kong. A clear labor shortage forecast is needed to understand both short-term and long-term shortages. To evaluate skill gaps, upskilling, training, and apprenticeships that will address the requirements of the current labor tasks as well as upcoming new skill sets brought by introducing automation and robotics technologies. The following section describes two proposed training strategies, in which the first one is focused on the training of front line workers and the second one is focused on the education and training of engineers and managerial personals. The construction industry needs to step up and find a feasible solution to attract more young people to work in the construction industry. In addition, by introducing new technologies, regulations and policies, a new set of market.

7.6.1 Education and training on worker's level:

- To establish training programs in-line with Hong Kong Institute of Construction (HKIC) frame work and scope, yet focus on introduction of the construction robotics so the existing work force will gain the basic knowledge of the given topic and potentially to achieve a career progression and advancement in professional level
- To provide collaborative training schemes in-line with the existing schemes
- To provide training program which is focus on on-site robotic operation and control and offer off-the-job training at the CIC training facilities as well as on-the-job training
- To provide health and safety training program to ensure safe human and robots collaboration
- To provide training program designed for robot maintenance and repair
- To provide an accreditation scheme for operating and maintaining construction robots

7.6.2 Education and training on the level of engineers and decision makers:

- To offer an interdisciplinary Master Course (e.g. offered by several Hong Kong based universities), which focus on construction robotics that allows specialization in the field. The Master Course will link up the industries and the academics that aims to solve highly practical issues. The future construction sector will expand to new business fields by absorbing advanced technologies from various disciplines. It can be considered as an incubator for strategic design and further development for the construction industry

7.6.3 Education and training for business creation:

- To encourage entrepreneurship in the filed
- To offer start-up supports, in terms of financing, licensing, marketing and networking
- To provide supports in commercialization of ideas and inventions
- To form a partnership with the existing associations e.g. with Hong Kong Science Park (HKSTP)

7.7 Facilitation of business creation, start-ups, and development of a robot supply and operation infrastructure

Geographically, situated next to Hong Kong, the Pearl River Delta Economic Zone, which consists of Guangzhou, Shenzhen, Dongguan, Foshan, Zhongshan, Zhuhai, Jiangmen, and parts of Huizhou and Zhaoqing, has been the most economically dynamic region of Mainland China since the “Open Door” policy. Astonishingly, Shenzhen, the next-door neighbor of Hong Kong, has transformed from a small fishing village to the biggest economy in southern China. In the first three quarters of 2017, the boomtown’s economic output rose 8.8 per cent year on year to 1.54 trillion yuan (US$232.66 billion). While the figure fell short of Hong Kong’s HK$1.94 trillion (US$248.27 billion) for the period but the gaps are narrowing (He, 2017). Shenzhen, which is home to numerous technology firms, including giants like Tencent, Huawei and DJI, all of which are known for their massive spending on R&D, saw its 2016 GDP figure rise by about 60 billion yuan to 2.01 trillion yuan. Evidently, in the recent years, Shenzhen based companies have spent a huge amount of R&D investment researching on robotics and Artificial Intelligence (AI), yet very few were focused on the topics of construction robotic and automation. This imposes great opportunities for the Hong Kong counterparts to join forces, collaborate and utilize resources in the Pearl River Delta Economic Zone region that can potentially bring mutual benefits to all parties. Furthermore, the collaboration can yield the next technology leap in the construction industry facilitated by Hong Kong’s technology expertise and Pearl River Delta Economic Zone’s manufacturing capability **(He, 2017)**.

7.8 Conclusions

Key insights and outcomes with regard to business strategy and market implementation recommendations:

1. Feature comparison between façade robot system and human labor is conducted.
2. Benefits of the robot system for the related stakeholders are revealed.
3. The business strategy for the façade robot system at current stage is described.
4. The cost reduction and payback time of the façade robot system with painting end-effector proposed in the report is estimated.
5. Education and training plan for workers, engineers, policy makers, and business people in terms of involvement in construction robots is drafted.
6. The facilitation of business creation, start-ups, and the development of a robot supply and operation infrastructure are considered.

8 Roadmap for future on-site robot technology deployment in the Hong Kong housing construction industry

A roadmap for implementing robotics and automation technology in Hong Kong's housing construction industry is critical for the future development of Hong Kong. The project roadmap demonstrates the current project that is almost completed, and the 4 follow-up projects (2A, 2B, 2C, 2D). The project roadmap describes the main phases, stages, and milestones that the follow-up projects need to go through in order to meet the future vision. The roadmap covers 3-time spans (Initiation, Follow-up Development, Future Vision), and was divided into 4 milestones. Please note that this is the initial draft of the project roadmap. The final roadmap needs to be drafted along with the key stakeholders, consortiums, and partners (see *Figure 8-1* on the next page).

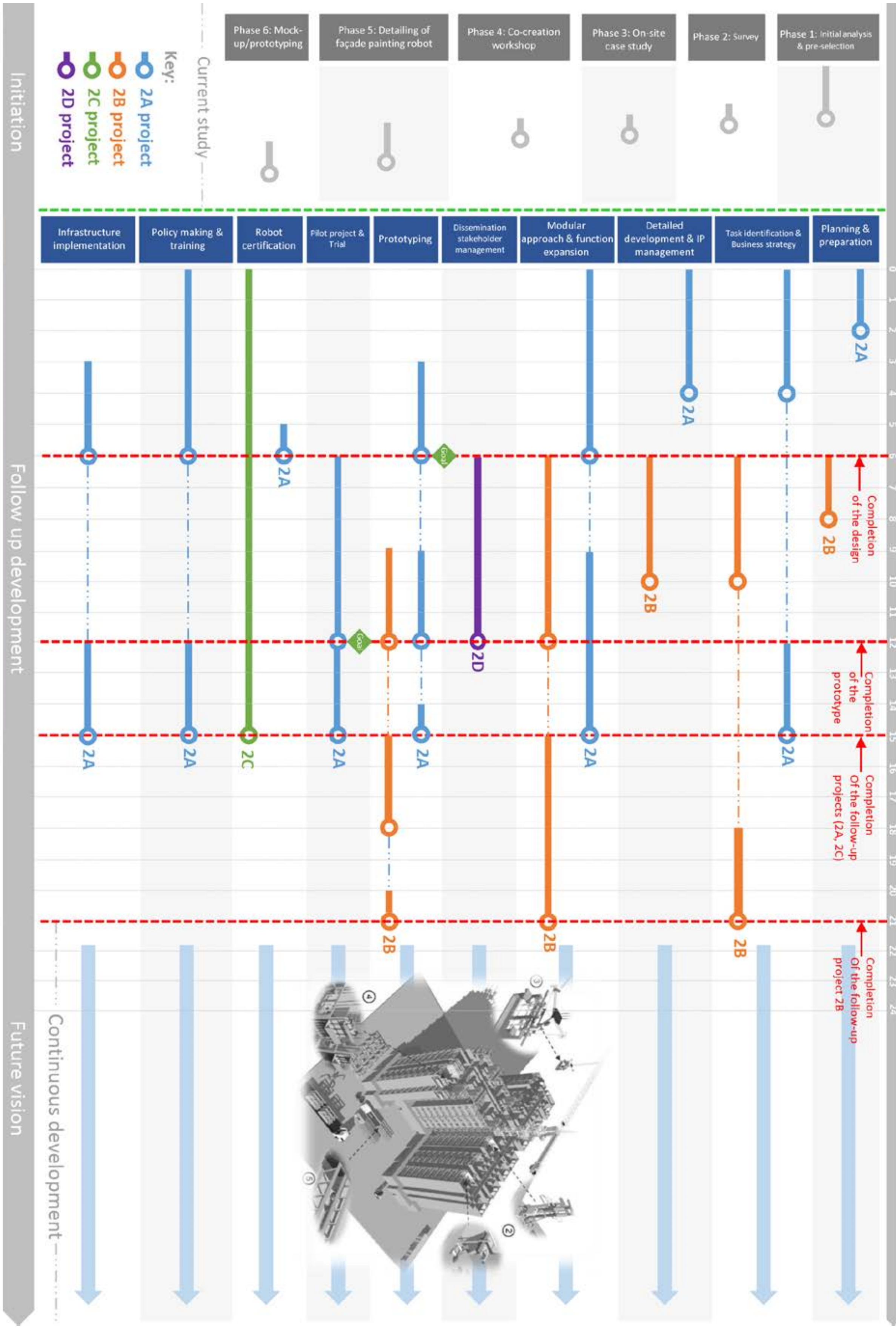


Figure 8-1: Roadmap for future construction robotic technology deployment in Hong Kong

In general, the overall roadmap consists of 4 identified Milestones.

- Milestone 1 (Month 6): Completion of the design (2A).
- Milestone 2 (Month 12): Completion of the 1:1 mock-up, and tested under pilot projects (2A). Successful organization of the workshop (2D). Completion of the design (2B).
- Milestone 3 (Month 15): Completion of 2A, 2C project. Successful delivery of the proposed system to TRL 6-7 (2A).
- Milestone 4 (Month 21): Completion of 2B project.

8.1 Project 2A: further developing an advanced mechanized construction tools with robotic feature (the façade-processing robot):

The objective of the 2A project is to finalize the proposed façade-processing robot base on the current development. The project team aims to bring the current design to Technology Readiness Level (TRL 7-8). A 1:1 scale functional demonstrator (mock-up) will be produced, ready for on-site pilot project, and testing. The mock-up will be transported to the dedicated pilot site for testing. The feedback from the on-site pilot project will be used for system optimization. By the end of the 2A project, the proposed system will be fully functional, on-site tested and ready for market dissemination.

The main sub-tasks involved in the 2A are:

- To detail design the proposed façade-processing robot, finalize the main frame, stabilization system, paint distribution, automated nozzle design, and to complete other final system integrations
- To produce the first basic testing range 1:1 scale demonstrator
- To conduct relevant trials under lab condition prior to on-site pilot project
- To carry out necessary training for the pilot project and trial
- To conduct the risk assessment and to mitigate potential risk
- To analyze the existing construction site infrastructure, identify whether or not the key area is suitable for implementation of the proposed system
- To install and calibrate the first demonstrator on the pilot site
- To test functionality and durability of the proposed system under real site condition
- To confirm the appropriateness and safety of any tools proposed and to confirm that any working practices are safe and comply with organizational/statutory standards.
- To evaluate benefits and constraints during implementation
- To document risks, issues and to recommend improvement strategy
- To test logistics, communication, and stakeholder management plans
- To evaluate the existing equipment and tools, and to propose an upgrade strategy
- To optimize the design based on the result of the first pilot project
- To finalize the design and upgrade the 1:1 scale demonstrator
- To conduct the second round of the pilot project
- To evaluate skill shortages that appeared during the pilot project and trial
- To propose feasible software and communication strategy
- To suggest additional training if needed

8.2 Project 2B: developing a fleet of construction robots mock-ups based on identified priority areas

The objective of the 2B project is to select appropriate systems that can be produced as scaled mock-ups with regards to the identified priority areas. The project team will conduct intellectual property related tasks, and to initiate patent application. TUM will work closely with HKSTP, and CITAC to accomplish these tasks. Currently, 2B project is only offered as an initial proposal.

The main sub-tasks involved in the 2B are:

- To design the selected systems in detail
- To determine the degree of freedom and automation based on the requirements
- To produce the mock-ups in an appropriate scale
- To test the basic functions and kinematics of the system and suggest potential improvement
- To formulate internal IP policies and administration of licensing and other agreement in regards to exploitation or collaborative, outsourcing and subcontracting issues
- To establish an IP portfolio, and to establish ownership or rights among the project team
- To design the user’s manual and safety manual for the mock-ups
- To install the mock-ups in CITAC’s exhibition center

8.3 Project 2C: training, standardization, certification

In the 2C project, TUM will closely work together with CIC to develop the training and standardization program for operating and maintaining the robot system. Certification of operating and maintaining the robot system for the trained workers will be issued by CIC. In order to ensure the training quality, the contractor/real-estate company needs to provide the training ground for the workers to practice in real-world conditions.

The main sub-tasks involved in the 2C are:

- To conduct research on global on-site construction robot certification topics
- To establish preliminary contacts with relevant stakeholders, such as Hong Kong Service Suppliers (HKSS), SGS Hong Kong for its Non-Destructive Testing (NDT), Electrical and Mechanical Services Department (EMSD), Hong Kong R&D Centre for Logistics and Supply Chain Management (LSCM), Hong Kong Green Building Council Limited (HKGBC) for its Building Environmental Assessment Method (BEAM), Environmental Protection Department (EPD), Hong Kong Housing Authority (HKHA), and Hong Kong Accreditation Service (HKAS) for its Product Conformity Certification Schemes (PCCS)
- To verify additional, possibly necessary certifications
- To check if all local, international standards are complied with and addressed
- To appoint official training providers and facilities

8.4 Project 2D, Dissemination stakeholder management

In the 2D project, TUM will work alongside with CIC in preparation of a two-day workshop. As proposed, the workshop consists of invited keynote speeches and roundtable discussions. The workshop focuses on the industry-driven research. The invited speakers need to demonstrate an innovative practical application that potentially solves a specific construction related issue in Hong Kong. A functional mock-up will be requested from the invited speaker and it will be displayed in the designated exhibition space.

The main sub-tasks involved in the 2D are:

- Organization of the workshop
- Networking & dissemination
- Management and logistics of the exhibits (Mock-ups)
- Exhibition preparation

8.5 Conclusions

Key insights and outcomes with regard to the development of a roadmap for future on-site robot technology deployment in the Hong Kong housing construction industry:

1. A roadmap for future robot technology deployment in Hong Kong's construction industry is proposed.

2. Key elements of the roadmap are explained for better understanding and usage.

3. Objectives and tasks in the 4 follow-up projects (Project 2A, 2B, 2C, 2D) are explained.

9 Summary, conclusions, and outlook

This report summarizes the key activities carried out and the results produced. First, the outcomes of an analysis of background, situation, and requirements are outlined. Second, the outcomes of the process of an identification of priority areas for the use of on-site robots is presented. This process includes the definition of basic scenarios, an online survey carried, an on-site case study identifying and analyzing construction processes potentially suitable for robotics use, co-creation workshops to detail requirements and functions of potential robotic solutions, and the analysis of potential priority areas. Third, the outcomes of an exemplary, technical detailing of the priority area “façade-processing” and the development of a prototype (mock-up) for demonstration and exhibition of the concept at CITAC are demonstrated. Fourth, the outcomes of the development of recommendations (with regard to process information modeling and business strategy) that flank the exemplarily detailed priority area are summarized. Last, a roadmap for implementing robotics and automation technology in Hong Kong’s housing construction industry as well as the strategy for conducting the follow-up projects are presented.

This report provides insightful knowledge of how to implement construction robotics and automation in the context of Hong Kong’s public housing construction sector. Thus, it is a valuable literature for the future research and development of construction robotics and automation in Hong Kong and other cities in China. In summary, the purposes, results, and key conclusions of each chapter in this report are listed in the table below (see *Table 9-1*). This table also serves as a tool for the readers to quickly retrieve the key points in each chapter of the report.

Table 9-1: Key results and conclusions of each chapter

Position in the report	Chapter title	Key results and conclusions of each chapter
Chapter 1	Structure of this report	• An overview of this project is provided. • The workflow of this study is explained. • The structure of this report is detailed to help the reader understand the report
Chapter 2	Background, situation and requirements	• A brief introduction to the history of construction robots is provided. • The existing issues of Hong Kong housing construction industry are analyzed. • The potential implementation of automation and robotic technology in the construction sector is described. • The study scopes of this consultancy that were agreed by CIC and TUM are clarified.
Chapter 3	Identification of the priority areas for on-site robot applications in Hong Kong’s public housing construction industry	• The methodology for identifying the priority areas in Hong Kong’s public housing construction sector is explained (e.g., pre-identification of technologies, online survey, on-site case study, co-creation workshop). • The 17 construction robotics and automation systems in

		three scenarios are initially identified. • The methodology and results of the online survey are revealed. • The key findings of the on-site case study of a Hong Kong housing construction project are described. • The process and results of the co-creation workshop are reported. • The method and decision of the final selection of 5 priority areas (i.e., façade processing robot system) are introduced.
Chapter 4	Exemplary detailing of priority area “façade-processing”	• The design of the proposed façade and exterior work robot system is revealed. • The changeable versatile plug-and-play end-effector system is introduced. • Three different modes of the robot to change the end-effector is proposed. • The various end-effectors and the applicable building types are proposed. • The positioning system of the robot is described and explained in detail.
Chapter 5	Development of prototype (mock-up) of the façade-processing robot for demonstration and exhibition at CITAC	• The detailed costs of manufacturing the fully functional prototype and the scale mock-up are explained. • The reason why the scale mock-up instead of full-size prototype is manufactured is explained. • The overall information of the scale mock-up (e.g. design, dimensions, functions, etc.) is introduced. • The details of all the mock-up components is introduced. • The demonstration and exhibition plan of the mock-up at CITAC is considered.
Chapter 6	Process information modeling (PIM) concept for efficient on-site robot deployment	• The background of Process Information Modeling (PIM) is explained. • The comparison of Building Information Modeling (BIM) and Process Information Modeling (PIM) is conducted. • The literature review of the key technologies in PIM concept is conducted. • The PIM concept development for external wall painting task is introduced. • Key outcomes and the future research roadmap for PIM concept are indicated.

Chapter 7	Business strategy and market implementation recommendations	• Feature comparison between façade robot system and human labor is conducted. • Benefits of the robot system for the related stakeholders are revealed. • The business strategy for the façade robot system at current stage is described. • The cost reduction and payback time of the façade robot system with painting end-effector proposed in the report is estimated. • Education and training plan for workers, engineers, policy makers, and business people in terms of involvement in construction robots is drafted. • The facilitation of business creation, start-ups, and the development of a robot supply and operation infrastructure are considered.
Chapter 8	Roadmap for future on-site robot technology deployment in the Hong Kong housing construction industry	• A roadmap for future robot technology deployment in Hong Kong's construction industry is proposed. • Key elements of the roadmap are explained for better understanding and usage. • Objectives and tasks in the 4 follow-up projects (Project 2A, 2B, 2C, 2D) are explained.
Chapter 9	Summary, conclusions, and outlook	• This chapter summarizes the purposes, results, and key conclusions of each chapter in this report • This chapter serves as a tool for the readers to quickly retrieve the key points in each chapter of the report.

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Appendix

Appendix 1: Pre-identification of potential technologies of Scenario 1

(1) Reinforcing bar fabrication positioning

a. Current situation

It was apparent that the amount of reinforcing steel required on a project on-site was proportional to concrete usage and the degree of structure design efficiency and the prefabrication rate with which it was applied to the concrete. The work activities, which related to reinforcement fabrication and positioning include the cutting, bending and tying of the reinforcement bar alongside handling and positioning the reinforcement bar accurately into the final position, such as on a floor mesh, in a mold or in a formwork situation. This type of task is extremely physical since the workers are more likely to be exposed to all weather condition and other potential hazards, therefore, it will significantly increase the on-site health safety related risk while carrying out such a task manually.

b. Proposed application

Automated systems will potentially decrease the aforementioned risks, improve working condition and enhance the productivity and quality of work related to reinforcement fabrication and positioning. The systems developed for this specific task include those for bending/shaping of individual reinforcing bars on-site and the interconnection (tying) of reinforcing bars to large reinforcement elements and meshes on-site. In the context of Hong Kong, an on-site application will be recommended. In contrast to the off-site reinforcement production factory, the systems used on-site are common to be highly mobile and compact to suit the purpose of temporary deployment. The main category includes small, mobile robots that can assist workers on the individual floors to handle, position, and tie up various sizes and weights of reinforcement elements. In addition, there is also a larger stationary system used for logistic, delivery, and positioning of the heavyweight reinforcement elements.

c. Case study 1: Robot for positioning of heavy reinforcing bars (Taisei Corporation)

This robot was developed to fabricate steel reinforcing bars on-site. It expedites reinforcing bar production and saves on required labor for the task. The system is not fully automated, as there are a few steps that still need to be completed manually. Required manual tasks include cutting and bending of longitudinal bars and stirrups, as well as laying down the top longitudinal bars. The robot then takes over the job, see *Figure 0-1*, until the fabrication of a steel reinforcing bar is complete, which then must be picked up manually.

Figure 0-1: View of total reinforcing bar fabrication robot system (Image: Taisei Corporation)

The robot (dimensions: H 1.70 m × L 8.50 m × W 1.50 m) marks the intersection of stirrups on longitudinal bars, places the stirrups at the designated locations and spacing, and secures them with binding wires. The system then locates the bottoms of the longitudinal bars and secures them by binding wire at the locations marked on stirrups. Then, the steel reinforcement is ready to be picked up manually and can be placed in a precast formwork to pour concrete. In contrast to conventional stirrups, which have open-ended hooks, this system uses closed-ended stirrups for automated flash butt welding to maintain bending quality. The robot is able to process a large variety of reinforcement dimensions within its workspace (reinforcement unit dimensions that can be processed: depth: 0.30–0.50 m, length: 4.00–6.00 m, width: 0.25–0.40 m) and needs about 4 seconds per intersection for binding.

d. Case study 2: Robot for positioning of heavy reinforcing bars (Taisei Corporation)

When vertical elements such as walls, columns, or pillars are constructed, reinforcing bars need to be added on top of each other and joined prior to molding and concreting. The reinforcing bars are usually joined by coupling sleeves. In conventional construction, both the positioning of the reinforcing bars as well as the coupling process require human labor, which are both physically demanding tasks.

Kajima's robot for the positioning and joining of vertical reinforcing bars assists the worker in handling and accurately placing the reinforcing bars, as well as in the installation/ fixing of the coupling sleeves, see *Figure 0-2*. It consists of a mobile, tracked platform, a manipulator, and an end-effector. The robot can be considered as a cooperative robot: the manipulator and the end-effector provide force assistance and are guided intuitively by one worker. The end-effector is able to both hold the reinforcing bar and to assist with fixing the coupling sleeve.

Figure 0-2: Robot for positioning and installation of medium-weight reinforcing bars (Image: Kajima Corporation)

(2) Automatic climbing formwork

a. Current situation

Conventionally, formwork is built on-site out of timber and plywood or moisture-resistant particleboard. It requires low tech for production by using basic hand tools, however, it is time-consuming for larger structures, and plywood facing has a relatively short lifespan. Furthermore, it usually takes up a huge amount of space on-site to store the formwork components. There are also many types of engineered/pre-fabricated formworks available on the market. This type of formwork is built out of prefabricated modules with a metal frame (usually steel or aluminum). The main advantage of this type of formwork are; increase speed of construction, steel form work can be installed and dismantled with greater ease and speed, steel formwork does not absorb moisture from concrete, and lower life-cycle cost.

Despite the advantages of the system, it is undeniably very labor-intensive when executing common formwork operations such as, propping, shuttering/de-shuttering, curing, cleaning and maintenance, see *Figure 0-3*.

Figure 0-3: Conventional formwork erection on-site. (Image: Hip Hing Engineering Co., Ltd, 2017)

b. Proposed application

In many regions around the world, the basic bearing structure of buildings is made of concrete. Despite the often either vertically or horizontally repetitive concrete structures that constitute the structural basis for concrete buildings, the process of building these structures with in-situ concrete is highly labor intensive, accounts for a large amount of the overall cost of construction, and builds on either (onsite) custom built or some kind of system formwork. An alternative to this approach provides – at least for high-rise buildings - high-end system formworks (also referred to as automatic or self-climbing formworks) of incumbent providers, such Peri or Doka that are equipped with some basic features for automating the climbing and formwork positioning process. Advanced features for such systems (such as additional sensors and activators or advanced digital control and commination capabilities) that would allow those systems almost completely autonomous self-alignment and climbing were the focus of research and development activities in the 1980s and 1990s, but failed to reach the product-grade level due to financial difficulties among other challenges.

c. Case study 1: Automatic climbing formwork SKE Plus (Doka GmbH)

Doka's SKE Plus series of automatic climbing formworks is used to produce large reinforced concrete structures such as cores of high-rise buildings, piers, pylons, and towers in a crane-independent manner. With its all-hydraulic equipment, see *Figure 0-4* and *Figure 0-5*, large platform gangs, such as all platforms on the outside of a core can be safely raised in a single lifting procedure without open fall hazard locations. The hydraulic lifting process requires two important steps. In the first step, the climbing profiles in the climbing shoes anchored on the structure are raised by the hydraulic cylinders to the next section. In the second step, the climbing scaffolds are pushed upward along the climbing profiles by the same cylinders. This type of climbing formwork is extremely versatile and allows for climbing inclines, radii, and bends. SKE plus provides multiple working platforms for simultaneous work at several levels, and if demanded, the possibility of complete enclosure for weather and noise protection.

Figure 0-4: Automatic climbing formwork SKE50 plus (Image: Doka GmbH)

Figure 0-5: Hydraulic climbing mechanism (Image: Doka GmbH)

d. <u>Case study 2: Platform system ACS P (Peri Group)</u>
Peri is one of the leading international companies in the formwork sector and, with its platform system ACS P a self-climbing system that allows for crane-independent and partly automated positioning and repositioning of formwork, provides for the on-site production of tower–like structures, see *Figure 0-6* to *Figure 0-8*. As either a single entity or divided into various segments the system is pushed upward floor by floor by a hydraulic mechanism. The system provides working platforms on different levels to parallel work activities. The system is strong enough to allow the lifting and storage of material, such as the reinforcement. If demanded, a concrete pump can be integrated and move upwards with the system. The ACS is a modular system formwork kit that can be customized by Peri and the clients into a large variety of tower structures.

Figure 0-6: The PERI climbing mechanism (Image: PERI GmbH, Weissenhorn)

Figure 0-7: ACS in action: The three core areas of the DC tower were moved up independently of each other using an ACS climbing formwork up to a height of 220 m. A 3.50-m concreting section was realized by the construction team in 4 days. (Image: PERI GmbH, Weissenhorn)

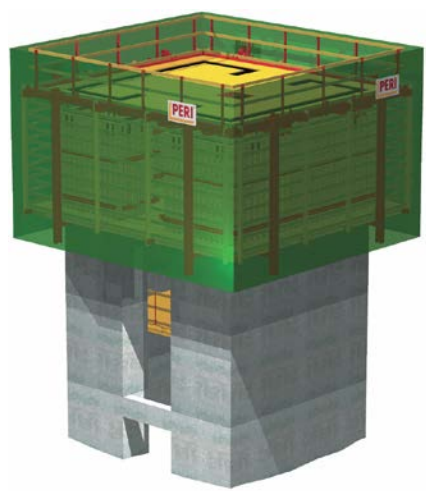

Figure 0-8: Outline of ACS P: The solution for advancing cores of high-rise buildings and tower-like structures. The platforms provide generous storage and working areas. With the ACS P system, only a few platform beams cross the walls. This means that the reinforcement can be partially prefabricated. (Image: PERI GmbH, Weissenhorn)

(3) Concrete distribution and finishing

a. Current situation

Ready-mixed concrete is a factory-produced construction material, locally supplied and transported as a fluid material ready for placing and compacting into any desired shape and size on construction sites. As we known, concrete is a complex material and due to its short shelf life, it is important that careful consideration of concrete supplier and the distribution process is made. In general, the concrete supplier will transport the ready-mixed concrete to the required site using his own truck mixers under instructions by the contractor, such as delivery time, dispatch time between trucks, etc. Then, the ready-mixed concrete will be pumped then poured into the pre-assembled formworks. The distribution of concrete by human workers can become a bottleneck operation slowing down the overall flow of work and material. Increase in resource efficiency within the concrete sector is an ongoing commitment focus of the construction industry.

b. Proposed application
Concrete distribution robots are used to distribute mixed concrete with uniform quality over large surfaces or over formwork systems and thus partly or fully automate a highly repetitive and labor-intensive task. The speed robots that can add to concrete distribution is also an important factor. The supply of concrete to a work area can be efficiently channeled using high-performance concrete supply pumps. The use of high-performance robots is complementary to the use of high-performance concrete supply pumps. Systems in this category range from horizontal and vertical logistics/supply systems to compact mobile concrete distribution and pouring systems that operate on individual floors as well as larger, stationary systems. In particular, the concrete distribution and pouring systems conduct simple and predefined (e.g., swaying) motions in a repetitive and accurate manner that are able to distribute the concrete uniformly. Most systems automate these simple repetitive motions, and overall guidance is needed in the work area through human intervention, thus indicating hybrid assistive systems rather than fully automated solutions.

c. Case study 1: Horizontal Concrete Distribution Robot (Takenaka Corporation)
This robot was introduced to improve and automate concrete distribution on individual floors. The robot has a relatively large workspace and can cover a work radius of more than 20 meters around the location where it is positioned, see *Figure 0-9*. It can be either fixed to a column or moved on the site by a mobile platform. The main body of the robot consists of a manipulator that can be lifted up and down (1 DOF) vertically and that consists of four segments connected horizontally through joints (thus providing another 4 DOF) as well as an end-effector that can fine position and sway the hose through which the concrete is pumped in a certain pattern. Takenaka showed that the system is able to reduce the required human labor by about 30%. The robot can be operated in an automatic mode and in a manual mode. The manual mode is used in areas containing a series of obstacles, making the correct positioning of the end-effector difficult. The automatic mode is used in areas with a relatively clear view and large obstacles.

Figure 0-9: Takenaka's horizontal concrete distribution robot in action

d. Case study 2: On-Site Concrete Logistics System (Konoike Construction Co., Ltd.)
Konoike's automated concrete distribution system, see *Figure 0-10* and *Figure 0-11*, is a solution for the optimization of concrete logistics on construction sites. It is particularly useful for very large or high-rise construction sites, where concrete pumps are difficult to use. The system consists of two robotic cranes (modified

standard cranes that were equipped with encoders), the climbing mechanism of the cranes, a concrete lifting container with integrated sensors and communication systems, and a concrete supply base. The concrete supply base can be considered as a type of fixture, which standardizes the locations for feeding and picking up the concrete-lifting containers on the ground level. This structure will supply concrete from the concrete lorry to the lifting container. Ready-mixed concrete trucks carry out concrete supply to the construction site as well as to the robot system in a timely and sequential manner. Therefore, the software system developed along with the robotic crane system allows integration with the supply chain, a real-time on-site monitoring system, and a programming and control interface.

Figure 0-10: Mobile concrete distribution robot (Konoike Construction Co., Ltd.)

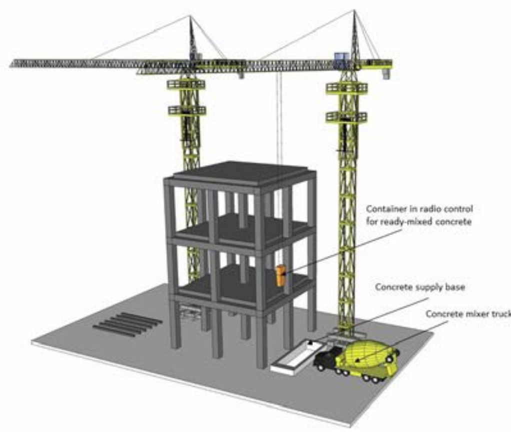

Figure 0-11: Overview of Konoike's automated concrete distribution system (Image: W. Pan)

(4) Concrete leveling

a. <u>Current situation</u>

Among various kind of construction work, concrete work remains one of the most common and important processes on most every construction site. Currently, a considerable amount of concrete structures are cast on-site. Importantly, however, concrete work is a labor-intensive job requiring considerable physical effort. Therefore, it is strongly desirable to automate and robotize concrete floor work including the leveling and screeding operations. In concrete floor work, the direct finishing method (monolithic method) was adopted in many construction industry around the world. Generally, this method is performed by professional workers according to the work procedure. Satisfactory completion of each step in the procedure is dependent on the skill and experience of the workers involved. As a result, three principal problems remain: 1) the workers must work hard in a squatting position, 2) the quality of the finished concrete floor depends on the workers' skill, and 3) the overall quality (including the levelness) has shown a tendency to be lower because of the increasing shortage of skilled workers, see *Figure 0-12*.

Figure 0-12: Conventional concrete leveling on-site (Image: www.impressionsconcreteandinterlock.com)

b. Proposed application
Automated or robotic concrete leveling and compaction systems are able to ensure uniform compaction (and thus concrete quality), and if properly integrated with other operations, allow enhancement of the overall speed of concerting works. Concrete leveling and compaction are frequently demanded and closely linked work activities on the construction site. Concrete leveling is the process of leveling the poured or roughly distributed concrete to have a more compacted and planar (but not finished) concrete layer. It involves a large number of repetitive operations (e.g., skimming with slide dampers). If manually done, continuous input of strong physical power is necessary, which limits the operational speed, making conventional labor-based concrete leveling a time- and resource-intensive construction operation. Automation of these operations – similar to concrete finishing operations – speeds up the process, enhances labor productivity, and maintains a highly uniform quality for the entire surface. Concrete compaction removes air from the concrete and compacts the particles inside the concrete mixes, which enhances the density and strengthens the bonding weaknesses between the concrete and reinforcement. Systems in this category are in most cases both leveling and compacting the concrete.

c. Case study 1: Floor Compaction System (Takenaka Corporation)
Concrete floor compaction is a critical process that needs to be done within a limited time following pouring. Therefore, speed and power are two important factors with respect to automating or robotizing this process. The concrete floor compaction system, developed by Takenaka, see *Figure 0-13*, consists of a main body, through which two plates are activated, creating a walking motion allowing the robot to move over an area of previously poured concrete. In addition, the two plates produce slight vibrations and thus apply a dedicated pressure to the surface. The robot thus is able to press out water from the concrete, compact it, and promote the hardening process. The robot is efficient in terms of the number of people required, the quality, and the time needed to complete the task. Furthermore, the efficiency of the system increases with the size of the floor area to be treated.

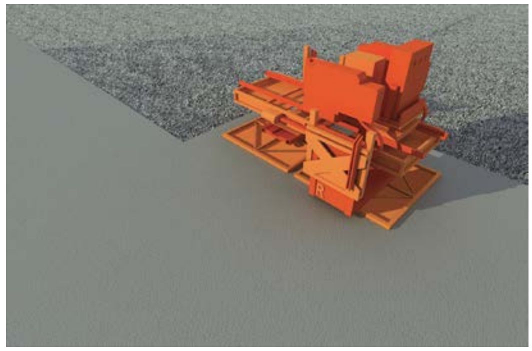

Figure 0-13: Concrete floor compaction system (Takenaka Corporation)

d. <u>Case study 2: Mobile Concrete Floor Finishing Robot (Shimizu Corporation)</u>
Conventionally, concrete pouring, screeding, smoothing, and finishing require a huge amount of manual handling, and the work can be physically strenuous. The Flat–KN, （see *Figure 0-14*) consists of three sets of trowel end-effectors located around a mobile robotic platform, a controller system that allows the robot to be either manually controlled or remotely operated, and an anti-collision device. The trowels are attached to the end of each retractable arm structure. The blade pressure against the floor can be adjusted in response to the hardness of the surface to be finished. The system is equipped with a portable control interface that is wirelessly connected to the robot allowing the operator to remotely control operation speed and orientation of the robot. In case of emergency, the touch sensor will guide the machine to avoid obstacles and switch off the machine automatically, when necessary. According to Shimizu, the concrete flooring finishing process can be divided into four stages that can be conducted by the robot system using different types of end-effectors: 1) primary finishing, 2) first finishing, 3) second finishing, and 4) final finishing. During the primary finishing stage, the trowel blades are disassembled and exchanged with leveling disks used to level and flatten the floor surface. The smoothing task is carried out during the first finishing stage by switching the leveling disks back to trowel blades. The blades are rotated as slowly as possible to protect the concrete surface. During the second finishing stage, the blades are adjusted to a faster speed to conclude the smoothing task. During the final stage, the robot inspects the surface and thus helps to assess the quality of the work done. A disadvantage of the Flat-KN is that it is difficult for the system to finish corners and edges between walls and floors because of its rounded shape, and these areas must be completed manually.

Figure 0-14: Flat-KN in action on the building floor (Image: Shimizu Corporation)

(5) Logistic supply

a. Current situation

Logistics operations on conventional construction sites, in particular those where many low-level parts must be handled, are numerous, time consuming, and involve hard physical work. Site logistics involve the identification, transportation, storage, and transfer (from one system or machine to another) of materials. Logistics operations follow at least along the main logistics routes on a construction site often clearly defined paths and the interaction of a logistic system with the often diverse materials can in many cases be standardized through the use of pallets and containers. Inefficient logistics and supply operation can potentially lead to delays in construction schedule, see *Figure 0-15*.

Figure 0-15: Conventional construction site storage (Image: www.lib.kobe-u.ac.jp, 2017)

b. Proposed application

In the Japanese construction industry, the automation of on-site logistics processes is becoming a standard event on the construction sites. This trend can inspire the development of on-site logistic and supply operation in the Hong Kong construction industry. Due to the similarity shared between Japan and Hong Kong, such as lack of on-site storage spaces as well as aging labor force. This category includes systems for the automation of vertical delivery of material, systems that allow a horizontal delivery of material on the ground or on individual floors, systems that assist with the transfer of pallets or material (e.g., from a lift to a mobile platform), as well as automated material storage solutions. Systems for horizontal delivery of material can comprise state forklift-like mobile robotic platforms, rail-guided ground-based or ceiling-mounted systems, or smaller micro-/mini logistics solutions. In all these instances, the control and navigation complexity is reduced significantly by operating the robots along fixed, predefined routes with standardized interaction points with other systems. Payload capacities of the individual systems range from around 100 kilograms for micro-/mini logistics solutions to several hundred kilograms for systems for horizontal delivery to several thousand kilograms for vertical lifts. Operation speeds are situated in a range between 40 m/minute and 100 m/minute.

c. Case study 1: AGV-Based On-Site Logistics System (Shimizu Corporation)

This on-site logistics system was designed for the delivery of construction materials such as plasterboards, fittings, pipes, ventilation components, and electrical components. The system consists of an automated vertical construction lift; an AGV; a control and scheduling system; and fixed, marked traveling routes, see *Figure 0-16*.

Figure 0-16: AGV transporting material from the automated construction lift to the assembly area on an individual floor (Image: Shimizu Corporation)

The AGV utilizes a mobile platform equipped with a fork lifting mechanism (capacity of 1300 kg) that allows it to take up and unload materials. It is equipped with an on-board battery power supply (it can be recharged at dedicated recharging locations to which it can automatically move) and can move only along fixed, marked trajectories, which significantly reduces the control and sensor complexity (i.e., no sophisticated sensors for navigation are necessary). As the operations of the lift and the AGV can be integrated and synchronized, it can be used on the ground floor to automate the delivery of material from a storage area into the lift and then to the individual floor level as well as the delivery of materials on floor levels from the lift to the assembly area. The vertical lift allows the AGV to move onto it for loading/unloading material or pallets. The system is thus able to fully automate the logistics on the site along predefined logistics routes.

d. <u>Case study 2: Automated On-Site Delivery System (Obayashi Corporation)</u>
The system was designed to reduce delivery costs and in particular enhance the efficiency of high-rise construction. The system consists of four main parts: 1) an automatic transfer equipment, 2) an automated guided forklift (AGF), 3) an automated storage rack, and 4) a web-based delivery scheduling system (WSS). The automatic transfer equipment is an intermediary system (capacity: 200 kgf) that can unload materials from a vertical construction lift to a dedicated location in front of the lift where the AGF can the take up the material, see Figure 17. Instead of using on-board battery power, the power for the automatic transfer equipment is provided through a flexible cable connected to the vertical construction lift's power source, thus minimizing its weight (800 kgf). The AGF has a lifting capacity of 1500 kgf, and has a compact chassis to be able to access all areas on the site. It runs on electromagnetically marked, fixed trajectories that connect dedicated load/unload area in front of the lift with other areas on the floor (e.g., the automated storage rack) where the AGF operates. The automated storage rack that is part of the system serves as an intelligent warehouse that operates without human interaction and allows for direct and automated interaction with the AGF, see *Figure 0-17* and *Figure 0-18*.

Figure 0-17: The automatic transfer equipment is an intermediary system that can both take up material from a dedicated location in front of a vertical lift to which the AGF has delivered material and unload a vertical lift (Image: Obayashi Corporation)

Deployed on the ground level the AGF can connect the automated storage rack with the automatic transfer equipment/vertical lift and thus automate the supply of material from the storage to an individual floor where the material is required. Deployed on an individual floor the AGF can automate the delivery of the material from the lift to the area where the material should be processed or assembled. The WSS consists of a terminal for application (TA), a web-shared server (WS), and a terminal for management (TM). The main purpose of the TM is data collection/input and delivery scheduling. These data are then uploaded to the WS so that the information is accessible for human workers and the automated equipment.

Figure 0-18: The AGF can directly interact with an automated storage system (Image: Obayashi Corporation)

(6) Hoist and positioning

a. <u>Current situation</u>

The transportation, elevation, balancing, and placement of materials in a conventional manner using a crane is not efficient and often leads to safety issues or material damages. Cranes are used primarily for logistics purposes, that is, transporting and placing materials on the floor or in the area where they are required, see *Figure 0-19*. However, for positioning and alignment operations, the components must often be picked up again and handled by another system and the flow of materials is thus interrupted. When lifting heavy component such as precast concrete, there are many challenges that exposed during the existing installation process.

Figure 0-19: Conventional construction tower crane (Image: www.camzhjx.com, 2017.)

Initially, the wall panels are off-loaded from the on-site stock yard or directly from the delivery vehicle by tower crane then lifted to the job floor where the panel will be installed into position. This task could be problematic as the tower crane can only lift one piece of panel at a time. While the tower crane is lifting the panel, the delivery vehicle has to remain stable on-site. This can cause two potential issues, first, down-time of tower crane time and second congestion on-site. The movement of the wall panel caused by swinging lifting hoist can make alignment and joining between the wall panel and the steel structural elements extremely difficult. Furthermore, damage on wall panel during assembly process can increase project cost and time delay dramatically.

b. Proposed application

Robotic positioning aids and robotic crane end-effectors improve conventional systems and methods, and allow for precise pick-up and position/alignment operations. Systems in this category range from relatively simple robotic end-effectors that allow only failsafe transport and the tele-controlled releasing of components to more complex systems that allow for rough positioning of a column or beam to highly complex multi-DOF end-effectors that allow accurate positioning and orientation of components. Some of the prototypes of the featured systems were in trials and demonstration also equipped with small, controllable turbines and gyroscopes to experiment with even more advanced features for position/orientation control. All the featured systems might serve as end-effectors for conventional cranes as well as for more advanced, automated logistics or carne solutions. The optimum system should be able to generate a continuing workflow, reduce downtime in every workstation and necessary waste, save investment, reduces expenses, improve the engineering quality and accelerate the overall construction process. The construction robot auto-shackle is used for the placement of large steel columns and beams, see *Figure 0-20*. The traditional method of placing these components requires labors to connect and disconnect the members from the crane shackle manually. This method is time consuming and dangerous, especially at great heights. The auto-shackle system allows this process to become automated and controlled remotely. The system consists of a main unit (with an integrated communication module, a control unit, and a rechargeable battery for power supply) and two clamps that through a controllable pin allow automatic release of steel columns once brought into the desired position, see *Figure 0-21*. It is controlled remotely via wireless communication through a control panel. The system is equipped with a limit switch that detects the locking state of the shackle pin.

Figure 0-20: Auto-shackle system in action (Image: Samsung and Kwangwoon University)

Figure 0-21: Detailed view of auto-shackle system (Image: Samsung and Kwangwoon University)

c. Case study 1: Auto-Claw (Obayashi Corporation)

Obayashi's Auto-Claw (see *Figure 0-22*) is a robotic end-effector that can be attached to standard and non-robotic cranes, thus adding some basic robotic features to their performance. The Auto-Claw allows a crane operator to pick-up, install, and release, in particular, mid-sized steel beam segments in a controlled manner. It simplifies the positioning/orientation and fine positioning of steel beam segments. The Auto-Claw speeds up the construction process and improves safety on the construction site as it eliminates the need for a worker to access the column and beam segments during the positioning process. The carrying capacity of the system is approximately 2 tons. A fail-safe system ensures that the lifted segments are not accidentally released in case of a sudden loss of power.

Figure 0-22: Auto-Claw (Image: Obayashi Corporation)

d. Case study 2: Auto-Clamp (Obayashi Corporation)

Obayashi's Auto-Clamp (see *Figure 0-23*) is based on the same principles and technologies as Obayashi's Auto-Claw. However, in contrast to the Auto-Claw, this crane end-effector is designed for the installation of heavier elements such as large steel columns. The Auto-Clamp is a robotic end-effector that can be attached to standard and non-robotic cranes, thus adding some basic robotic features to their performance. The Auto-Clamp allows a crane operator to pick up and release, in particular, large column segments and it simplifies the positioning of those segments. The Auto-Clamp speeds up the construction process and improves safety on the construction site as it eliminates the need for a worker to conduct work at the top end of the column during the positioning process. The carrying capacity of the system is approximately 14 tons. A fail-safe system ensures that the carried segments are not accidentally released in case of a sudden loss of power.

Figure 0-23: Auto-Clamp (Image: Obayashi Corporation)

(7) Installation and material handing

a. Current situation

Facade installation operations include the positioning and adjustment of windows, complete facade elements, or exterior walls of a building. Facade elements, in modern architecture and especially in high-rise construction, are decoupled from the bearing concrete or steel main structure and can thus be considered as a type of "infill" or "platform" system. Facade installation operations are complex operations that involve the accurate positioning of heavy parts or elements at locations that are difficult to access (e.g., high altitudes without scaffolding). This involves the risk of injury (and thus requires extensive safety measures) and of damaging expensive elements. Furthermore, the positioning and alignment of prefabricated facade elements requires precision with low tolerances for error. This is extremely difficult and time consuming when executed with the conventional construction method, see *Figure 0-24*.

Figure 0-24: Conventional material handling on-site (Image: www.reader.us, 2017)

b. Proposed application
Since the 1980s, the growing trend of designing large buildings as monolithic structures repeating similar facade elements has provided a major incentive for investment into the development of automated or robotic systems. Up to the present day, facade installation systems have been a hot topic in R&D departments, especially firms in Asia where high-rise buildings are becoming more and more prevalent, even in residential construction. Systems in this category include mobile robots that is lightweight and can be used on the individual floors to install facade components and other building elements from the floor level.

c. Case study 1: Element Installation Robot (Kajima Corporation)
The installation of facade elements can be a hard and dangerous task for human workers. It requires dealing with heavy panels and installing them carefully in the correct location and position. It often requires three to four workers inside the building and a crane working outside of the building, carrying the panel to the desired floor and holding it until the workers finish the installation process. The facade element installation robot by Kajima makes this process much easier and cheaper. It reduces the number of workers needed inside the building to one or two and ends the need for cranes to position the load from outside the building. The robot has a compact design and is movable, allowing it to be easily transported to the site and to the desired floor using conventional on-site construction lifts. The robot consists of a mobile platform that can lift and lower a manipulator and an end-effector that can pick up, hold, and lower facade panels through a winch mechanism. The robot allows thus to lift the elements into the desired position and keep them precisely in that position until a worker can fix it in place, see *Figure 0-25*.

Figure 0-25: Facade element installation robot system operated on the finished floor (Image: Kajima Corporation)

d. <u>Case study 2: Concrete Panel Installation Robot (Kajima Corporation)</u>
Based on the Kajima LH series robots, Kajima's facade concrete panel installation robot system is equipped with a specialized end-effector for picking up, transporting, and positioning of comparably small facade panels. The robot system allows a single worker to conduct the installation process by manual remote control of the system, see *Figure 0-26*.

Figure 0-26: Facade concrete panel installation robot, installing facade panel (Image: Kajima Corporation)

(8) Façade coating and painting, exterior finishing application

a. Current situation
Painting of building façade is a challenging task, which, even with the help of scaffolding are still difficult to gain access. Facades of high-rise buildings, in particular, are difficult to paint or repaint during construction, as well as during operation. Conventionally, workers have to be placed in a swinging stage, which provides vertical movement for workers working in painting, spraying, caulking, sash-sealing, cleaning, etc.; in general for all the external finishes of a building, see *Figure 0-27*. Because of the swinging stage will be suspended over the external façade of the building, there is no weather protection for the workers, therefore, during high wind or raining conditions the exterior work task on a high rise building become even more difficult.

Figure 0-27: Conventional facade painting operation (Image: www.shutterstock.com, 2017.)

b. <u>Proposed application</u>
Facade painting robots were developed to simplify the painting of building facades, especially for high-rise building. Facade painting robots have a particular advantage in keeping the quality constant. They usually have multiple spray nozzles operating in a synchronized mode. The nozzles are also usually encapsulated or housed within covered elements to prevent the escape of paint. The continuous painting quality is specifically controlled by the precise control of the spray nozzles, spraying

speed, and spraying pressure. Another major advantage of painting robots is the fact that the workers are not exposed to harmful paint substances. STCRs for painting use different strategies to move along the facade such as suspended cage/gondola mechanisms, rail-guided mechanisms, and mechanisms allowing movement along the facade by vacuum or other adhesion technology. Facade painting robots are therefore used primarily to paint large facades of high-rise buildings and larger types of commercial buildings. Facades to be painted are in general required to be rectangular, and to have no corners or profile structures that could hinder the operation of the robot. Furthermore, the design of the window frames as well as the amount and area covered by the windows impact the applicability and efficiency of facade painting robots.

c. Case study 1: Robot for Painting Exterior Walls (Taisei Corporation)

The robot for painting exterior walls (see *Figure 0-28* and *Figure 0-29*) from Taisei is used for the automated application of paint to the facade of a high-rise building. The system allows for improved efficiency and accuracy as well as reduced risk as manual labor at extreme heights is not required. The system consists of three main components; a mobile, rail-guided robot unit (vertical movement along the facade; speed: 8 m/minute descending, 16 m/minute ascending) equipped with a mechanism that moves the actual panting end-effector, horizontally, a roof-mounted unit from which the robot unit is suspended (this unit also integrates a control cabin as well as tanks to store panting/coating material), and a paint supply component that transports paint from the roof carriage to the robot unit.

Figure 0-28: Robot traveling along the faced through facade-integrated rails (Image: Taisei Corporation)

Figure 0-29: Overview of robot for painting exterior wall system (Image: Taisei Corporation)

The robot moves vertically along the face of the building along guiderails that were previously integrated into the building's facade. The painting end-effector of the robot is housed within a dedicated compartment such that no excess paint escapes. Eight rotating airless-type spray guns of the end-effector apply paint in a precise and efficient manner. The thickness of the paint/coating applied can be accurately controlled and adjusted. A series of sensors allow the robot to paint accurately around facade elements such as windows. A single operator through the control cabin that is part of the rooftop unit supervises the system. Paint/coating material is supplied from the tanks of the rooftop unit through a hose to the main unit. After each vertical section is completed, the robot is relocated through the roof unit (that can travel horizontally along the rooftop) to the next vertical section. The robot is able to achieve a painting rate of about 100 m^2/hour.

d. Case study 2: Facade Painting Robot System (Kajima Corporation)

In contrast to other painting robot systems, this robot system is not suspended from the top of the building; but rather, it is based on a gantry-type kinematic structure oriented horizontally along the wall, see *Figure 0-30*.

Figure 0-30: Facade painting robot system (Image: Kajima Corporation)

The robot system is able to coat and/or paint large surfaces of a building. It consists of the gantry-type positioning system, a covered spraying chamber, a robotic manipulator placed inside the spraying chamber, a system for storing and supplying the paint (installed on the ground and able to pump the coating/painting material to the spraying chamber),and the spraying gun end-effector. The gantry-type positioning system allows the actual spraying system (housed in the covered spraying chamber) to be moved at relatively high speeds all over the facade. The gantry-type positioning system consists of a vertical mast (installed between temporary installed rails that are fixed between the roof and a mobile, robotic carriage on the ground of the building).The mast can be guided by the rails and the motorized carriage moved horizontally along the wall. Along the mast, the painting chamber can be moved in the vertical direction. Inside the spraying chamber, the spraying gun end-effector is moved by a rail-system–based manipulation system back and forth (z-direction), left and right (x-direction), and up and down (y-direction). Once positioned by the gantry-type positioning system this system can thus cover a work area of 4 × 1 meters. When one work area is fully processed, the system is repositioned by the gantry-type positioning system. The work procedure always starts at the top of the wall and the spraying chamber is repositioned until one vertical wall/faced segment is processed. Following this, the next vertical (4 m broad) wall segment is processed. A sensor system detects irregularities in the wall and thus allows the system to paint walls containing windows or others design features. The system is able to perform coating/painting with a processing rate of up to 200 m^2/hour and special textures spraying with a processing rate of up to 100 m^2/hour.

(9) Exoskeleton

a. Current situation

Handling heavy load manually was a common exercise in the construction industry. However, due to demographic change in many developed countries, there is fewer younger workers are willing to engage in heavy physically demanding tasks. In addition, handling heavy load can potentially cause personal injuries or even fatal accident and compensation claimed by effected construction workers can lead to financial ruin or administration of a company.

b. Proposed application

Exoskeletons, wearable robots, and other assistive, cooperative robots and devices allow, through direct cooperation between human beings and the robot system or device, to combine the flexibility and intelligence of human beings with the strength, speed, precision, and endurance of machines and robots. The approach, on the one hand, makes it possible to circumvent many of the challenges associated with other types of robots (e.g., no need for full automation or complex locomotion or navigation strategies and thus definitely much easier to develop and implement than humanoid robots) and on the other hand introduces new challenges in terms of biosensors, human–robot interaction, and control algorithms required. Full-body exoskeletons that embrace the whole human body are the most capable but also most complex form of wearable robots. In particular for manufacturing or construction purposes such exoskeletons may be equipped with additional handling devices or mini cranes.

c. Case study 1: Exoskeleton for Handling Heavy Steel Elements (Daewoo Shipbuilding and Marine Engineering [DSME])

DSME's exoskeleton is made from carbon, aluminum, and steel, weighs 28 kilograms, and is fully self-supporting, meaning that the worker wearing the suit is freed from the weight of the exoskeleton itself. It is powered by hydraulic and electric activators that allow the exoskeleton a lifting capacity of up to 30 kilograms (which is beyond what the human worker has to handle).Moreover, the exoskeleton can be equipped with a variety of task-specific add-on frames that turn the exoskeleton into a mini crane for material handling, see *Figure 0-31*. At the back of the exoskeleton a battery pack is installed that allows for up to 3 hours of operational time. The goal of the company is to improve the capability of the exoskeleton so that in the future it will be able to take over loads of more than 100 kilograms. Although Daewoo developed this exoskeleton in the context of shipbuilding, its use in the near future in other divisions of Daewoo, such as its construction division (Daewoo E&C), is highly likely. It is common in the Japanese and Korean industries, where companies usually hold divisions of many industry branches, that, for example, welding robots developed in the shipbuilding division are transferred to the construction division later on.

Figure 0-31: Daewoo's exoskeleton being tested in the context of handling heavy steel (Image: Daewoo)

d. Case study 2: Fortis Exoskeleton (Lockheed Martin)
FORTIS is a relatively simple, unpowered (containing no active motors), and lightweight exoskeleton. The idea is that heavy handheld construction devices or end-effectors such as welding tools, sandblasters, and grinding machines can be fixed to an additional mechanical arm extending from the exoskeleton, see *Figure 0-32*. This arm then allows these devices or end-effectors to be fixed conveniently in certain positions and their load transferred to the ground over the exoskeletons. Furthermore, a device on the back of the exoskeleton allows balance weights to be added, which in addition makes it possible to counterbalance the weight of the tool fixed to the extended arm. Workers can thus endure certain positions longer and without fatigue, and also usually awkward positions become ergonomically feasible. The FORTIS exoskeleton is considered by Lockheed Martin as a transitional device to more advanced exoskeletons with active motors. Although the device is not for sale yet, it is likely that this exoskeleton (as it contains no active motors or sensors) will be available for a price far below that of other exoskeletons on the market.

Figure 0-32: FORTIS exoskeleton equipped with a grinding tool (Image: Lockheed Martin, 2015)

Appendix 2: Pre-identification of potential technologies of Scenario 2

(1) Mobile on-site factory

a. Proposed application
A mobile on-site factory can be rapidly deployed on the construction site and once the construction project is complete, the mobile factory will be delivered to the next building site by Lorries. The on-site factory can be used for producing precast concrete element such as, precast staircases, floor, and wall elements. The advantages of the mobile on-site factory are include, production of the building element is in close proximity to the building site, just-in-time production, limited space requirement and low initial investment costs, high mobility with low assembly and disassembly costs and simple operation and high reliability through simple technology.

b. Case study 1: MBM The mobile battery mold
This new product development of Weckenmann Anlagentechnik allows the production of flat precast concrete parts in the immediate vicinity of the construction site. The challenges of the 21st century include rapid population growth and increasing urbanization worldwide. This requires to build more and more large residential complexes even faster. Large construction sites for the construction of new residential areas or entire cities are temporary and generally do not allow that conventional stationary precast concrete plants are set up in the immediate vicinity of the construction site. Central precast plants often experience long transport routes and therefore they are too uneconomical. In addition, long transport routes

carry bigger risks, the goods may be damaged or traffic problems may lead to delays in delivery. Some countries also don't have the necessary infrastructure and transport capacities. Stationary concrete plants require in addition large investments and quite frequently their realization fails due to lack of financial means. For the developers from Weckenmann, all of these requirements form the basis for the construction and development of the Mobile Battery Mold, see *Figure 0-33*. The use of this mobile battery mold allows the vertical production of flat precast concrete parts in form of a field factory.

Figure 0-33: MBM in operation at a site in Singapore (Image: www.weckenmann.com, 2017)

The battery mold as a stationary form in the production of precast concrete elements has the following principal advantages:

- simple and easy-to-use manufacturing process,
- the concrete surface of walls and slabs has a finished surface that is smooth on both sides,
- compact design, thereby higher volume output and small floor space requirements,
- insensitive to varying qualities of concrete through highly efficient compaction device,
- Energy efficient through best use of hydration heat for the curing process and the ability to heat the mold intensely.

The battery mold is basically composed of:

- a fixed middle part,
- two movable external molds with electric motor drivel
- several (usually 18 units) mobile intermediate forms
- vertical side mold and horizontal bottom mold depending on the thickness of the element
- electric vibrators for the concrete compacting are integrated in the mold frame, and are powered by a frequency converter for the infinitely variable speed regulation
- heating coils, that are also arranged within the mold for a fast curing of the concrete
- a hydraulic power unit and two hydraulic cylinders for the closing of the mold

The technical solution foresees that a battery mold is built on a special vehicle in form of a semitrailer, which can be moved by standard tractors. The special vehicle is used to transport the heavy central and outer mold. These central elements of the battery mold and other plant components such as control, heating and hydraulic unit are fixed mounted on the special vehicle. The additional working platforms as well as the intermediate forms and other small-scale equipment components will be transported on conventional vehicles from site to site. A suitable lifting gear is necessary in addition to the mobile battery mold. This lifting gear is required to mount the battery mold, but it must also assume all necessary load movements in the running production process. Those task can be handled by either by a gantry crane or a conventional rotating tower crane or a mobile crane. A lane is necessary for the gantry crane, which can be based on strip footings or on transportable footing beams. An oil- or gas-operated heating is located on the special vehicle that provides hot water for the battery mold, if needed. A mobile tent on the crane way can protect the battery mold against extreme weather conditions (rain or heat). The setup and dismantling requires approximately five qualified employees for only few working days, depending on the situation on site, see *Figure 0-34*.

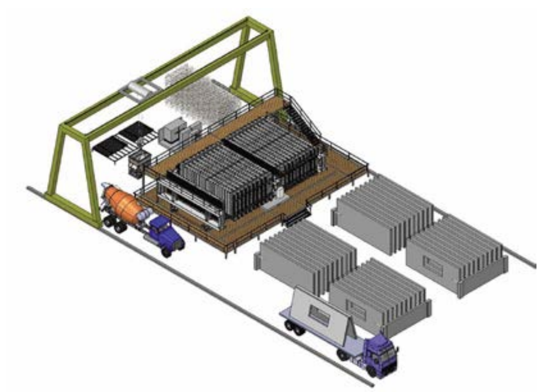

Figure 0-34: Components of the mobile factory (Image: www.weckenmann.com, 2017)

(2) Vertical delivery system

a. Proposed application

The type of the delivery system that is described here is typically mast-based, normally situated on the exterior façade of the building, which provide vertical material transportation from the storage space to the job floor. In general, the vertical delivery system will be used in conjunction with the hoist and other logistic systems. The vertical delivery can relieve the job loads of the existing tower crane so that the tower crane will be concentrate on dealing with other construction tasks.

b. Case study 1: Automated Construction Lift (Obayashi Corporation)

This automated vertical logistics solution can be used as a separate system on the construction site, as well as in combination with other STCRs (e.g., robotic forklifts, automated guided vehicles [AGVs], etc.), creating a larger material supply solution on the site, see *Figure 0-35*.

Figure 0-35: Automatic vertical lift (Obayashi Corporation)

Obayashi also used the system in the context of its automated/robotic on-site factories. The system consists of two masts that allow lifting and lowering of the logistics compartment. The guiding masts are fixed to the ground as well as at certain heights to the building. The system allows the supply of small as well as large material (e.g., columns, beams) and construction equipment (including other STCRs). The logistics compartment is loaded on the ground level from material delivered from the storage area or by delivery truck by means of forklifts, cranes, or human workers. Following this, the logistics compartment lifts the components to the required floor level, where it can be unloaded. If required, two or more systems can be operated in parallel to guarantee an uninterrupted material supply.

c. Case study 2: Automated Vertical Material Delivery Lift (Kajima Corporation)
The Automated Vertical Material Delivery Lift System was developed with the intention to arrange vertical transportation of goods on a construction site without the necessity of tower cranes, see *Figure 0-36*. It is arranged so as to provide a continuous flow of construction materials, tools, and other elements. The system consists of a set of rails mounted to the outside of the building on which a logistics unit is operated in vertical direction. The logistics unit allows one to pick up standardized containers and compartments (placed under it or directly from delivery trucks or forklifts) from atop. It then delivers these containers to the floor where the material is required and transfers it through a cantilevering, telescopic transfer mechanism into the floor onto a delivery template. The system can be used in renovation and building disassembly/deconstruction projects.

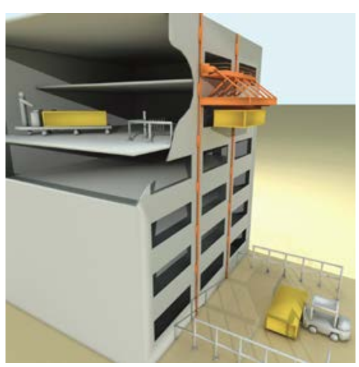

Figure 0-36: Overview of Automated Vertical Material Delivery Lift (Kajima Corporation)

(3) Floor slab, beam, column positioning and handling system

a. <u>Proposed application</u>
This category of positioning system is usually used as an integrated system of the sky-factory. The system is relatively simple robotic end-effectors that allow only failsafe transport and the tele-controlled releasing of components to more complex systems that allow for rough positioning of a floor element, column or beam to highly complex multi-DOF end-effectors that allow accurate positioning and orientation of components. The systems that featured here can be used as an end effector for conventional crane, or function as a gantry crane on top of the building, which is to be erected. The optimum system should be able to generate a continuing workflow, adoptable, collaborative, reduce downtime in every workstation and necessary waste, save investment, reduces expenses, improve the engineering quality and accelerate the overall construction process.

b. <u>Case study 1: Robotic End-Effector for Big Canopy (Obayashi Corporation)</u>
This robotic end-effector (see Figure 0-37 and *Figure 0-38*) developed by Obayashi for its automated/robotic on-site factory, Big Canopy, is conceptually and in terms of embedded technology similar to the Auto-Claw and the Auto-Clamp. In contrast to the Auto-Claw and the Auto-Clamp, this robotic end-effector is designed, in particular, for the handling of various types of prefabricated concrete elements. Similar to the other systems mentioned, this system consists of robotic end-effectors that can be – aside from its utilization within the Big Canopy – attached to standard and non-robotic cranes, thus adding some basic robotic features to their performance. The system allows a crane operator to pick-up, position, orient, and release concrete elements.

Figure 0-37: Robotic end-effector for Big Canopy system (Image: Site Automation, 2016)

Figure 0-38: Overview of the sky factory Big Canopy system (Image: Site Automation, 2016)

c. <u>Case study 2: Robotic Crane End-Effector Mighty Jack (Shimizu Corporation)</u>
The robotic crane end-effector Mighty Jack by Shimizu is a steel beam positioning manipulator used for the placement of medium-sized steel beams, see *Figure 0-39*. It has dimensions of L 6.70 – 7.80 m × W 1.00 m × H 1.40 m, a weight of 1800 kilograms, and a hanging load capacity of 1500 kilograms. The end-effector can be attached to conventional as well as advanced, automated cranes, lifting mechanisms, or overhead manipulators (OMs), and allows improving the cycle time and safety of the assembly procedure. The end-effector (activated by hydraulic activators) contains two grippers at its ends that allow it to be fixed between two columns a lifting mechanism to handle (including lift and lowering) of the steel beams to be placed, and a telescopic mechanism that allows it to adjust to a variety of distances between columns. The system is lifted into place (already holding the beam to be placed), for example, by a tower crane. The two grippers at the ends of the end-effector allow the system then to attach to the columns of the already built steel structure segments, use them as a reference framework for the beam positioning, and adjust its position. Following this, the steel beam is lowered by the end-effector in a controlled manner to the desired position between the two columns and the beam component released automatically once demanded. The steel beam is fixed to the surrounding steel structure by conventional labor-based methods. The control approach is a hybrid between fixed sequence control and wireless tele-operation.

Figure 0-39: Mighty Jack system in action

(4) Façade element installation

a. Current situation

Glass glazing façade element (glazed curtain walling) is widely used as finishing material for many buildings to ensure aesthetics of the architectural appearance of the project. The trend of the glazed curtain walling is becoming larger and heavier and it is more challenging to install such element manually. In general, during the process of installing heavy façade materials on buildings both inside and outside, that the handling of the materials has been mostly executed by using cranes or pulleys, whereas assembly and installation have been mostly done by construction workers manually, see *Figure 0-40*.

Figure 0-40: Conventional glazing curtain wall installation (Image: www.halfen.com, 2017)

b. Proposed application

The proposed concept will demonstrates collaboration between group of STCRs, vertical transportation system and integrated storage, logistics system. The proposal will reduce manual task, improve safety on-site, increase productivity, eliminates the need for scaffolding or the use of the conventional crane. The document will describe two systems that include the Shuttle System for the Installation of Facade Elements developed by Fujita Corporation and Brunkeberg System, developed by Brunkeberg Systems AB.

c. Case study 1: Shuttle System for the Installation of Facade Elements (Fujita Corporation)

The shuttle system from Fujita is used for the easy installation of large exterior wall elements such as curtain wall panels. The system consists of a stage (end-effector) that surrounds the perimeter of the building, vertical guiderails for the stage to be lifted, and motor driven chain blocks that provides the ability to lift the stage, see *Figure 0-41*.

Figure 0-41: Shuttle system in action (Image: Construction Robots, 2016)

With this system, an entire floor of large amount of work that usually has to be done on the floor level and under inconvenient and dangerous work conditions and also eliminates the need for scaffoldings and cranes. The system is equipped with a laser distance sensor that measures the distance to the approaching stage five times per second to prevent collision and ensure a safe positioning and connection of the lifted facade segments to the segments above.

d. Case study 2: Brunkeberg System (Brunkeberg Systems AB)

The Brunkeberg System partly automates the logistics and installation of façade panels, see *Figure 0-42* and *Figure 0-43*. Key parts of the system are the profiles attached to the main building structure for fixing the facade panels, the facade panels, and the logistics and installation mechanism. The profiles attached to the main building are designed to allow guidance of the mechanism for automated vertical delivery of the facade panels. However, the panels themselves also contain features that facilitate their handling by the logistics and installation mechanism. The panels are delivered by trucks to a logistics yard on the site where the logistics system picks them up and delivers them to a buffer storage. From there the panels are distributed hanging on rails by a horizontal delivery system (HDS) to the segment of the façade where they have to be installed. Guided by profiles attached to the main building structure, a vertical delivery system (VDS) takes them up from the HDS and delivers them vertically to an installation area where, assisted by a human worker, the panels are installed. Brunkeberg is backed by large companies such as Lindner Group of Germany and aims at both speeding up material logistics and reducing human labor input.

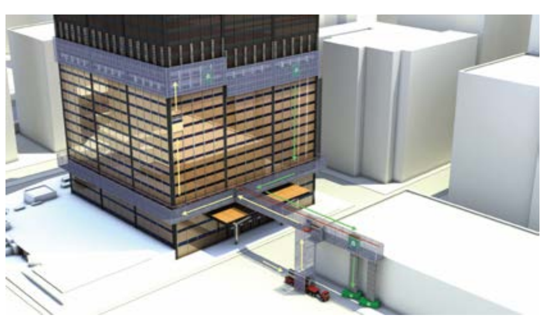

Figure 0-42: Outline of logistics and installation strategy

Figure 0-43: Material handling yard on the ground

(5) Prefabrication in HVAC system

a. <u>Current situation</u>

Assembly of building services on a busy building site can be very challenging. Many contractors such as electrician, plumber and installation engineer have to work side by side to ensure on-time delivery of the project. This is often difficult to deliver due to poor management and miscommunication between trades. The HVAC equipment is often supplied by an individual supplier this lead to risks of delay, higher logistics costs. Once the equipment arrives on-site they are expose to the risk of accidental damage while they waiting or during the installation process. In addition, skill shortage and demographic change also exhibit increasing challenges on assemble building services on-site.

b. <u>Proposed application</u>

The off-site manufacture of building services modules represents the lowest risk method of the delivery and installation of services to the construction site. The ability to simultaneously manufacture building components with the site work, allows the project team the flexibility and time to take advantage of just-in-time delivery. There are many advantage of prefabrication in HVAC system, for example, accuracy in production, reduce embodied energy, on-site logistics and reduce installation time. Yet, the biggest benefit of prefabricated HVAC system is improve planning and collaboration between all involved parties.

c. <u>Case study 1: University Medical Center project in New Orleans</u>

An extensive prefabrication strategy aims to keep the $1-billion University Medical Center project in New Orleans on target to meet the project's daunting scope and aggressive construction schedule. To help keep pace, almost 40% of the mechanical systems at the project site are being prefabricated in racks up to 8 ft (3.44m) wide and 20 ft (6m) long. Each one of the 1,100 racks contains HVAC ductwork, utilities, piping, cabling and relevant mechanicals for each floor, see *Figure 0-44*.

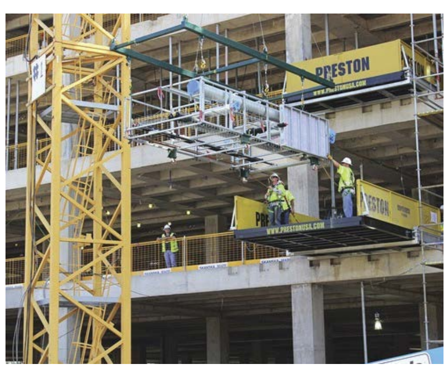

Figure 0-44: Installation of the HVAC ductwork (Image: www.enr.com, 2017)

The construction company built an onsite fabrication shop and secured a warehouse across town. At its peak, the offsite shop had 120 workers staffing three assembly lines that were constructing up to 90 racks simultaneously. Austin says the shop has framers, plumbers, pipe fitters, electricians, insulators, welders and HVAC specialists working side by side in a manufacturing-type environment, see *Figure 0-45*. Because of the heavy use of prefabrication, it was dramatically increased on-site assembly time, improved safety and kept the project on schedule.

Figure 0-45: Factory-prefabricated HVAC component (Image: www.enr.com, 2017)

d. Case study 2: The Leadenhall Building London

The Leadenhall Building in London at 47 stories and 225 meters high, which is the highest office building in City of London and one of the highest prefabricated building in the UK. The building service steel table are 100% prefabricated off-site in a controlled factory environment in Enniskillen, Northern Ireland. It acting as a structural core for the building. Because the structural core is situated on the north side of the building, hence the project team call it the north core. The north core was reconfigured structurally into three table elements per floor level. The prefabricated steel table will be transported to Wolverhampton, England after the paint job is dried off. There, the steel table was fitted with all mechanical, electrical, plumbing and HVAC system, finally closed off with precast concrete slab on top. If this task was conducted in the conventional manor, it will be impossible to meet the project dead line at the end, see *Figure 0-46* and *Figure 0-47*.

Figure 0-46: Installation of the prefabricated steel table (Image: www.designcurial.com, 2017)

Figure 0-47: On-site assembly of the prefabricated HVAC system (Image: www.ctbuh.org, 2017)

Appendix 3: Pre-identification of potential technologies of Scenario 3

(1) Sky factory

a. Proposed application

Integrated automated construction sites can be categorized according to various features or characteristics, such as general working directions, logistics strategies, climbing mechanisms, or configurations of the site factories. It is also possible to characterize them according to manufacturing views (organizational view, product variation view, order-oriented view, or location-oriented view).

The general working direction and thus the location and workflow orientation of the factory and the location of the majority of work activities play a major role in manufacturing of buildings and determine logistics strategies and factory configurations. As buildings are complex and large products that require a final assembly on the fixed, final site, the orientation of the building and thus the location and working direction on-site determine the general organizational setting and thus the logistics strategy, climbing system (CS), and factory configuration.

b. Case study: Big Canopy (Obayashi Corporation, Japan)

Big Canopy was designed by the Obayashi Corporation in 1995 and it was the first automated construction system applied in the construction of precast concrete structures, see *Figure 0-48*. The Big Canopy itself was supported by four masts independent of the building. By placing the structure outside the building, it allowed more flexibility than other systems had previously. Once the floor was erected, the canopy is jacked up one story at a time and always left a two-story space in between the canopy and the on-site factory floor. The Parallel Material Delivery System consisted of overhead cranes and material delivery lifts. Overhead cranes were operated by workers on the factory floor using joystick control kits. The method was more cost effective than applying a fully automated delivery system. The Big Canopy system was the first automated construction system which improved overall productivity and it has been applied to several projects. The system achieved a huge reduction in rate of labor and in use of materials. Moreover, it showed the potential for automated construction systems; they can be flexibly altered with the shape and design of the building. Although applying automated construction systems is still not considered cost effective, it has shown its potential when it is used repeatedly. Construction automation has the capability to change every perspective of the construction industry. It could also generate many new business opportunities and demand a new generation of construction proletariat.

Figure 0-48: Big Canopy by Obayashi Corporation (Image: Site Automation, 2016)

(2) Ground on-site factory

a. Proposed application

Systems in this category are characterized by the installation of a fixed, ground-based on-site factory for the erection of horizontally oriented buildings that are long and/or wide horizontally, while at the same time relatively flat.

b. Case study: System Skanska

The Swedish construction group Skanska has developed this system for the automated construction of horizontally oriented buildings (such as, e.g., condominiums) which are the predominant building typology in Europe, see *Figure 0-49* and *Figure 0-50*.

Figure 0-49: Horizontal delivery system of the ground on-site factory

The system utilizes a fixed GF in which rail-guided and ground-based robots operate in a structured environment. The operations are more horizontally oriented and the building is built up from prefabricated concrete wall panels instead of columns and beams. The evolution sequence can be characterized as follows: 1) installation of GF and ground-based robots/HDS, 2) floor assembly on the ground, 3) pushing up of the assembled floor, and 4) repetition of processes 2) & 3) and parallel interior finishing.

Figure 0-50: Lifting after assembly of ground floor (Image: Skanska)

The ranges of End-effectors include, Ground-based HDS (rail-guided assembly robot) can be equipped with various end-effectors, necessary for picking up concrete components. Owing to the high-degree of standardization of the concrete components, so far only one end-effector has been required. However, if greater variety is required, additional exchangeable end-effectors can be developed.

(3) Integrated automated on-site assembly system

a. Case study: Universal Construction System (Technical University of Munich [TUM])
   M.Sc. W. Pan from TUM developed the UCS concept as part of his master thesis in 2013, see *Figure 0-51*. Systematically, the UCS can be divided into four categories: structural, component, production and construction.

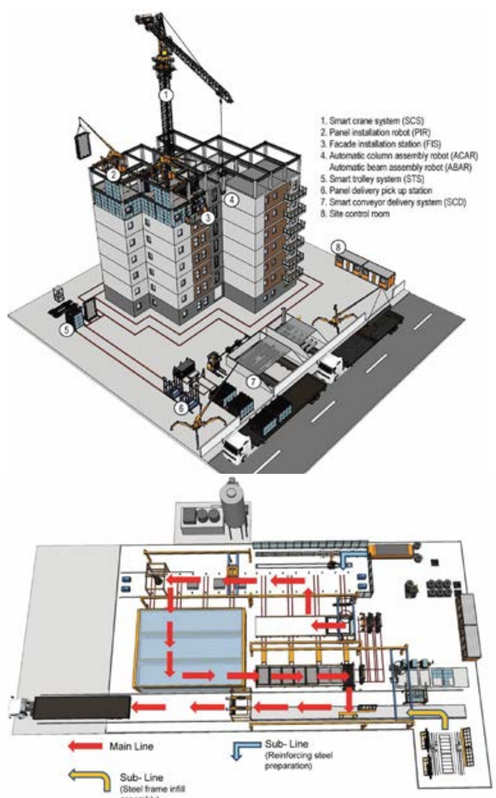

Figure 0-51: UCS construction system and production system (W. Pan, 2013)

In general, structural systems include a series of beams and columns that are interconnected and provide a flexible box-shaped support system. Component systems contain wall elements, floor elements and interior fixtures plus services of the building. Each part can be easily assembled or disassembles to allow the building system to be upgraded regularly. Production systems involve off-site manufacturing of all UCS building elements. An on-site field factory concept for different site scenarios will also be considered. Construction systems consist of all on-site technological, managerial and operational all on-site assembly activities. A range of construction equipment and single-task construction robots were included by the author in order to increase overall construction efficiency. One approach for designing UCS construction robots is to utilize existing robot and machine tools, rather than develop a system from scratch. Most of the modern construction equipment has the potential to be controlled remotely or achieve fully automated operational functionality by performing a minimal software or hardware makeover. The approach reflects the economical affects proposed by the concept. It will save massive amounts of initial R&D costs and encourage construction firms to engage in the development of construction robotics.